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Report No. FAA-RD-78-51

75th ANNIVERSARY OF POWERED FLIGHT 1903-1978

AD A061859

IMPACT OF AREA NAVIGATION ON CONTROLLER PRODUCTIVITY AND ATC SYSTEM CAPACITY

ERIC H. BOLZ

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DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

JANUARY 1978
FINAL REPORT

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
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16. Abstract

This report provides a detailed analysis of the impact of Area Navigation (RNAV) on ATC controller's tasks and the resulting productivity of control sectors, and of the impact on airport and enroute system capacities. The results are expressed in terms of projected savings in ATC controller staff growth requirements (man-years and dollars), and in terms of savings in aircraft delays (aircraft time and fuel consumption, and dollars). The terminal area and enroute (high and low altitude) environments were considered separately.

The analysis considered the time period from 1982 to 2000. The effects of other features of the Upgraded Third Generation ATC System on controller tasks and system capacity were considered directly in each analysis. All dollar results were computed as 1976 present value equivalents which were used to update a comprehensive RNAV benefit/cost analysis from an earlier report under this contract.

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METRIC CONVERSION FACTORS

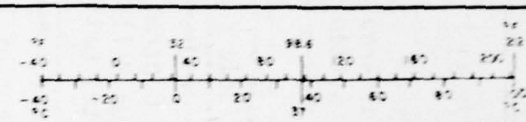
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The Systems Research and Development Service of the Federal Aviation Administration has undertaken a program to assess the technical and economic impact of Area Navigation on the ATC System and the users of the National Airspace System. This work was performed under the RNAV Technical Support Contract to Systems Control, Inc. (Vt), Contract No. DOT-FA72WA-3098, Task Order No. 015. The work was performed by the Champlain Technology Industries (CTI) Division of Systems Control, Inc. (Vt).

The FAA Technical Monitor for this work was Ricardo Cassell, ANA-200, and the Technical Support Program Manager was D.W. Richardson of Systems Control, Inc. (Vt). The Project Manager and author of this document was E.H. Bolz of Champlain Technology Industries Division of Systems Control, Inc. (Vt).

This document is the final report containing the results of studies of the impact of RNAV on controller productivity and ATC system capacity, including the effects on delays and airline fuel consumption.

TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

LIST OF FIGURES

LIST OF FIGURES - Continued

LIST OF TABLES

LIST OF TABLES - Continued

LIST OF TABLES - Continued

LIST OF TABLES - Continued

LIST OF TABLES - Continued

1.0 EXECUTIVE SUMMARY

This section presents a summary of the study objectives and results in a compact format. Also, the study conclusions are briefly reviewed in this section. The detailed analyses of controller workload and productivity effects are found in Section 2, and traffic capacity and delay analyses are found in Section 3. Section 4 presents the study conclusions in detail.

1.1 PROGRAM OBJECTIVES

The primary objective of this task is to quantify the effects that the introduction of RNAV will have on controller productivity and system capacity. The benefits and costs to the system users and to the ATC system itself are also to be quantified, based on the present work and on a prior comprehensive cost/benefit analysis (reference 1) performed as Task Order No. 013 under this contract. The productivity and capacity effects to be expected in the terminal, high altitude enroute and low altitude enroute environments are to be quantified separately, although the methodology adopted for use in this study analyzed the low and high altitude enroute environments in parallel. The impacts of 2D, 3D and 4D area navigation were to be considered separately, as appropriate. However, the RNAV concept has recently evolved (reference 2) to the point where 3D (VNAV) capability is considered to be a useful pilot aid capability, but will not be used to provide procedural separation or for routine radar control. Therefore, no controller productivity impact would result, but user cost/benefit values pertaining to 3D RNAV derived in that reference remain unchanged.

Two primary outputs are required from this study:

1) The productivity impact of RNAV translated into controller staffing requirements, with man-year savings projected to the year 2000, and

2) The capacity impact translated into delay savings, with fuel and time savings projected to the year 2000.

In particular, the overall energy-use savings due to reduced delays is of interest. These projections of RNAV effects have been calculated considering an orderly RNAV implementation process beginning in 1982. Also, and of extreme importance, the assumed operating environment considers an orderly implementation of all remaining UG3RD features, up to and including DABS Data Link and Control Message Automation. In this fashion, the effects of these other UG3RD features on controller productivity, capacity and delays, and their interaction with RNAV, have been properly considered in order to prevent over-estimation of RNAV impact.

This study represents a considerable refinement to earlier work performed in the areas of RNAV impact on controller productivity and system capacity. The first productivity analyses conducted under this contract are discussed in reference 3 (unpublished) which interpreted the results of a real time New York area simulation study which considered RNAV as one of several ATC improvements included for study. It concluded that productivity improvements of 10% (terminal) and 14% (enroute) would result from the implementation of a 100% RNAV environment. These data were interpreted in order to estimate staff savings, as reported in reference 2 and later reiterated in reference 1. These figures did consider the impact of other UG3RD programs implicitly by basing staffing savings on a staff level projection over the UG3RD implementation

period, but did not supply detailed analysis of the interaction of each UG3RD program on the RNAV percent benefit. The most recent report, reference 1, interpreted these results in terms of the 1976 present value equivalent savings. The current study evaluates the RNAV interaction with each individual level of UG3RD enhancement, and provides yearly staff savings projections considering an orderly UG3RD implementation process to the year 2000, and derives the total present value equivalent to those savings.

Likewise, reference 2 provides an analysis of arrival delay reductions resulting from 4D RNAV capacity improvements. Interactions with other UG3RD programs were analyzed only in gross terms. The most recent report, reference 1, interpreted these same results in terms of the present value equivalent. The current study considers the arrival capacity improvement potential of RNAV alone, and of RNAV with 4D as well. Also, capacity improvements due to the other UG3RD enhancements, and interactions of the enhancements with RNAV capacity improvement potential, are considered. A yearly delay savings projection considering an orderly UG3RD implementation process, plus the present value equivalent, are provided. Fuel savings are expressed in terms of quantity saved as well as value.

The overall ATC system user present value benefit/cost ratio analysis resented in reference 1 has been revised. These new results are presented in Section 1.3.4. The conclusions reached as a result of this study are summarized in the section below.

1.2 SUMMARY OF CONCLUSIONS

This study has shown that several of the UG3RD features, including RNAV, can provide significant enhancements to the controller's ability to handle

traffic, through reductions in controller workload, and will produce significant savings in terms of staff requirements by reducing the rate of growth of the ATC staff as traffic demand increases. The study results show that, over the 19 year period considered, RNAV will produce a savings of 3715 man years (terminal) and 20,498 man years (enroute), equivalent to $92 million and $508 million respectively, based on the 1975 salary level.

This study has also shown that real terminal arrival capacity improvements result from usage of the RNAV capability in the conventional ATC environment, and from the usage of the 4D RNAV capability in a Metering and Spacing environment. These capacity improvements amount to 3.26% and 4.6% respectively. The savings to the air carriers in terms of fuel and aircraft operating time costs over the 19 year period will range between $2.5 and $4.2 billion dollars, depending on values assumed for fuel and aircraft time costs. RNAV usage could also result in savings in enroute delays if controller staff growth is artificially constrained such that enroute delays increase. It is of interest to consider the implication of terminal delay reductions in terms of raw fuel consumption. The savings over 19 years based on the phased implementation of RNAV and 4D RNAV in terminal operations will be 3.77 billion gallons, equivalent to 52% of the total 1975 air carrier fuel consumption. Based on analyses in reference 1, the total anticipated fuel savings due to RNAV (delay reduction, terminal routes, enroute routes, VNAV) will amount to 11.35 billion gallons, more than 1.5 times total 1975 air carrier fuel consumption.

1.3 STUDY RESULTS

In this section the results of each major area of study will be presented. These include workload/productivity results and their staffing

implications (terminal and enroute), and capacity and resulting delay effects and their fuel and time value savings implications. Also, the overall 1976 present value RNAV benefit/cost ratios derived in reference 1 will be updated.

The basic approach to the workload/productivity analysis was to adapt a controller workload analysis methodology developed by SRI (references 4, 5 and 6) in order to include the effects of RNAV. The SRI technique provided a background analysis of the present ARTS III (terminal) and NAS Stage A (enroute) environments, plus additional analyses of each environment with several levels of planned UG3RD enhancements. These enhancement levels are discussed in detail in Section 2, but are listed below in Table 1.1.

Table 1.1 UG3RD Enhancement Levels Considered

TERMINAL	ENROUTE
1. Basic ARTS III	1. Basic NAS Stage A
2. Automatic Flight Data Handling	2. Automatic Flight Data Handling
3. Metering and Spacing	3. Automatic Local Flow Control
4. Conflict Probe	4. Sector Conflict Probe
6. DABS, Control Message Automation	6. DABS, Control Message Automation

The levels listed are cumulative in that each level includes those before it, as would be the case in a time-ordered enhancement implementation process. The fifth level considered by SRI was RNAV. However, since it was considered desirable in this study to determine the impact of RNAV on controller productivity for <u>each</u> enhancement level, the original Level 5, RNAV, does not appear on the list. By analyzing RNAV impact with each individual enhancement level it becomes possible to totally separate the RNAV implementation schedule

from the UG3RD feature implementation schedule implicit in the sequence of enhancement levels shown in Table 1.1. Instead, the RNAV implementation schedule originally derived in the RNAV Implementation Report (reference 2), which is summarized in Section 2.1.2, has been utilized. In both the terminal and enroute cases the SRI techniques provide methods for interpreting the results of the workload analyses in terms of controller productivity impacts and, in turn, controller staffing requirements. Furthermore, these results have been generalized to provide overall results for twenty-six major terminal areas and all twenty enroute centers.

1.3.1 Workload and Productivity

Terminal Area Workload Results (Oakland Bay TRACON Case Study)

The impact of RNAV on controller workload for each type of sector (feeder, final and departure) serving the San Francisco airport was calculated for each UG3RD enhancement level studied. Routine workload, conflict processing workload and surveillance workload factors were all considered. Workload is measured in terms of man-seconds of effort per aircraft handled at a given level of traffic demand. Table 1.2, below, lists the overall workload results for the Bay TRACON case. The values stated are averages for each of the two feeder, final and departure sectors serving SFO. Besides raw workload data, the percentage improvements due to RNAV and due to each successive UG3RD enhancement are listed. The RNAV workload impact for the feeder sectors is approximately 8%, dropping to 5% as the UG3RD enhancements are added. The RNAV effects for the final and departure sectors are larger: 15% (dropping to 7%) for the final sectors, and 23% (dropping to 17%) for the departure sectors. The impacts of the UG3RD enhancements (without RNAV) are highly variable, with some being very significant. However, the RNAV impact is shown to be more significant than any other UG3RD enhancement for the departure sectors, and

Table 1.2 Terminal Control Sector Workload Summary (One Man Sector Team)
(Man-Seconds Per Aircraft Handled)

	SECTOR TYPE										
	FEEDER					FINAL			DEPARTURE		
UG3RD ENHANCEMENT LEVEL	0% R	100% R	RNAV %	R + 4D	R+4D %	0% R	100% R	RNAV%	0% R	100% R	RNAV %
1. Basic ARTS III	78.4	72.0	8.1%	--	--	70.1	59.9	14.5%	75.9	58.7	22.6%
2. Flight Data Handling	75.5	69.1	8.4%	--	--	66.0	55.9	15.4%	67.1	50.0	25.5%
% Improvement	3.7%					5.8%			11.5%		
3. Metering & Spacing	64.5	60.3	6.6%	56.5	12.4%	52.9	44.7	15.5%	67.1	50.0	25.5%
% Improvement	14.5%					19.9%			0.0%		
4. Conflict Probe	64.5	60.3	6.6%	56.5	12.4%	52.4	44.7	14.7%	63.1	48.9	22.6%
% Improvement	0.0%					0.9%			5.9%		
6. DABS/CMA	49.6	46.7	5.9%	44.5	10.5%	36.0	33.6	6.6%	56.9	47.5	16.6%
% Improvement	23.1%					31.3%			9.8%		

Heading Key:

0% R -- No Aircraft Are RNAV-Equipped
100% R -- All Aircraft Are RNAV-Equipped
RNAV % -- Workload Improvement Due To RNAV
R + 4D -- All Aircraft Are 4D RNAV-Equipped
R+4D % -- Workload Improvement Due To 4D RNAV, Compared To No RNAV

to be in third place in level of impact for the feeder and final sectors. The usage of 4D RNAV integrated with a metering and spacing system significantly improved the overall effect of RNAV on feeder sector workload, essentially doubling the impact. The 4D feature had no effect on final and departure sector workload.

Table 1.3 lists the sector capacity results of this study for the one-man team case. The capacity of a sector has been defined by SRI in reference 4 as being the point where the radar controller position workload reaches a threshold, determined to be 48 man-minutes in an hour in the experiments which SRI conducted. The capacity table is somewhat abbreviated in that only the RNAV impact percentages, not raw capacities, are listed. The overall trends shown are similar to the workload case shown in Table 1.2, but the absolute magnitudes are somewhat different. As before, RNAV with 4D in an M&S environment tends to double the basic RNAV effect for the feeder sectors.

Enroute Center Workload Results

In this study nine enroute and transition sectors were selected in the area surrounding the Atlanta terminal area in the Atlanta Center. Based on SRI analyses of enroute ATC (reference 5) the RNAV impact on workload and sector capacity was determined in a manner somewhat analogous to the terminal area study, except that there is an additional constraint in the definition of sector capacity besides the 48 man-minute constraint on the radar man: if the two primary controllers (radar and data men) perform workload in excess of 66 man-minutes in an hour, the sector is also said to be saturated. Each of the nine sectors were evaluated separately and the two capacity criteria were applied in order to determine which constraint applied. For purposes of brevity, the raw workload data results are not presented here. Rather, the

Table 1.3 Terminal Control Sector Capacity Effects (One Man Sector Team)
(Aircraft Handled Per Hour)

UG3RD ENHANCEMENT LEVEL	SECTOR TYPE: FEEDER 0% R	FEEDER RNAV %	FEEDER R + 4D %	FINAL 0% R	FINAL RNAV %	DEPARTURE 0% R	DEPARTURE RNAV %
1. Basic ARTS III	36.8	6.8%	--	41.1	13.1%	38.0	28.1%
2. Flight Data Handling	37.9	6.9%	--	43.0	13.6%	42.2	34.2%
% Improvement	3.0%			4.8%		11.1%	
3. Metering & Spacing	44.6	7.0%	14.1%	54.1	19.2%	42.2	34.2%
% Improvement	17.8%			25.6%		0.0%	
4. Conflict Probe	44.6	7.0%	14.1%	54.7	17.9%	44.8	30.4%
% Improvement	0.0%			1.1%		6.3%	
6. DABS/CMA	58.0	6.3%	11.7%	79.1	8.4%	49.5	21.5%
% Improvement	30.0%			44.7%		10.5%	

Heading Key:

0% R -- No Aircraft Are RNAV-Equipped
RNAV % -- Workload Improvement Due To 100% RNAV Participation
R+4D % -- Workload Improvement Due To 100% 4D RNAV Participation, Compared To No RNAV

capacity results only are presented in Table 1.4 since they are more directly applicable to the end result objective: staffing requirements.

The capacity results for the basic NAS Stage A Case in Table 1.4 are based on the 2.5 man sector staff configuration, which is reasonably typical for a busy sector. Since the first UG3RD feature eliminates the assistant position (0.5 man), UG3RD enhancement levels 2 thorugh 6 were evaluated using a two man team. The capacity improvement due to RNAV in the high and transition sectors for the NAS Stage A base case ranged from 11% (Arrival Transition) to 21% (Departure). These values were comparable (but slightly less) than the other two UG3RD feature categories studied which showed significant benefi[illegible]) Automatic Flight Data Handling and Automated Local Flow Control, an[illegible]S/CMA. The fact that the RNAV impact is nearly commensurate with the DABS/CMA impact is in contrast to the terminal area case, where RNAV lagged significantly. The last sector shown in Table 1.4, Low Enroute, was evaluated at a 50% RNAV participation level and so its RNAV impact is considerably less. The RNAV effect in each case holds up as the UG3RD features are introduced through level 4. However, when level 6 (DABS/CMA) is introduced the percent RNAV effect is diminished somewhat, on the order of 25%. A similar trend occured in the terminal area case. The major cause is related to the fact that many routine navigation, route and conflict related controller tasks are automated.

1.3.2 Controller Staffing Implications

Terminal Facility Staffing

Linear least square fit techniques were utilized to produce relationships of controller staff required to serve SFO operations relative to the present staff size, versus traffic growth ratio, as shown in Figure 1.1. Based on an

Table 1.4 Enroute Control Sector Capacity Effects (2.5/2.0 Man Sector Teams)
(Aircraft Handled Per Hour)

SECTOR TYPE

UG3RD ENHANCEMENT LEVEL	High Enrt.		Dep. Trans.		Departure		Arrival	
	0% R	RNAV %	0% R	RNAV %	0% R	RNAV %	0% R	RNAV %
1. Basic NAS Stage A	41.6	11.8%	38.4	13.5%	50.6	21.1%	30.3	14.8%
2,3. AFDH, ALFC	47.1	12.0%	44.8	13.2%	66.1	20.4%	36.1	14.9%
% Improvement	13.3%		16.8%		30.6%		19.1%	
4. Sector Conflict Probe	49.9	12.0%	46.9	13.3%	67.1	20.5%	38.2	14.3%
% Improvement	5.8%		4.6%		1.5%		5.8%	
6. DABS/CMA	57.9	7.9%	52.9	9.2%	78.4	15.3%	45.2	12.3%
% Improvement	16.2%		12.7%		16.8%		18.3%	

	Arr. Trns.		Low Arr.		Low Enrt. *	
	0% R	RNAV %	0% R	RNAV %	0% R	RNAV %
1. Basic NAS Stage A	36.5	10.8%	35.1	12.8%	33.1	5.8%
2,3. AFDH, ALFC	42.2	12.0%	39.8	12.6%	38.2	7.3%
% Improvement	15.8%		13.5%		15.2%	
4. Sector Conflict Probe	45.5	11.0%	41.9	12.5%	40.0	7.3%
% Improvement	7.7%		5.3%		4.9%	
6. DABS/CMA	52.2	8.1%	47.3	9.9%	45.8	6.3%
% Improvement	14.8%		12.8%		14.4%	

* Only 50% RNAV Participation is Assumed in the Low Enroute Environment

Heading Key:

0% R -- No Aircraft Are RNAV-Equipped
RNAV % -- Workload Improvement Due To RNAV

assumed UG3RD feature and RNAV implementation scenario, a projection of staffing requirements at twenty-eight TRACONs has been performed, using the relationships in Figure 1.1. The implementation scenario assumed states that, beginning in 1980, enhancement levels 2, 3 and 4 are phased into full operation by 1985, and that DABS/CMA (level 6) is phased in by 1990. RNAV equippage by air carriers is projected to be phased in from 1982 to 1985 [1], with 4D operations beginning in 1986. General aviation operators are assumed to equip at half that rate. The twenty-eight TRACON staffing requirement is summarized by year in Table 1.5. The overall savings due to the 19 year period RNAV is in use is 3715 man years, or 14%. At 1975 wage and benefit estimate [7] of $24,795 per controller, this amounts to a total savings of $92.1 million. Standard FAA staffing formulas provide for additional support personnel over and above actual controller staff [8]. The proportionality constant is roughly 22% for terminal facilities. Therefore, staff savings would increase accordingly.

Enroute Center Staffing

The relationships of staffing requirements to traffic demand growth factor were determined by applying a fast time simulation technique using the increasing traffic capacity of a contiguous set of sectors in the Atlanta Center as each sector is split into two smaller sectors, and determining the number of splits required to service a given level of traffic while maintaining average enroute delays encountered at a constant level (present level of service). The result of such analysis is a set of staffing requirement versus traffic level factor curves. There is one curve for each enhancement level, and a second curve for each enhancement plus RNAV, as shown in Figure 1.2. It also shows the curves for the level 1, 3.5 man case, labeled 1B, since the

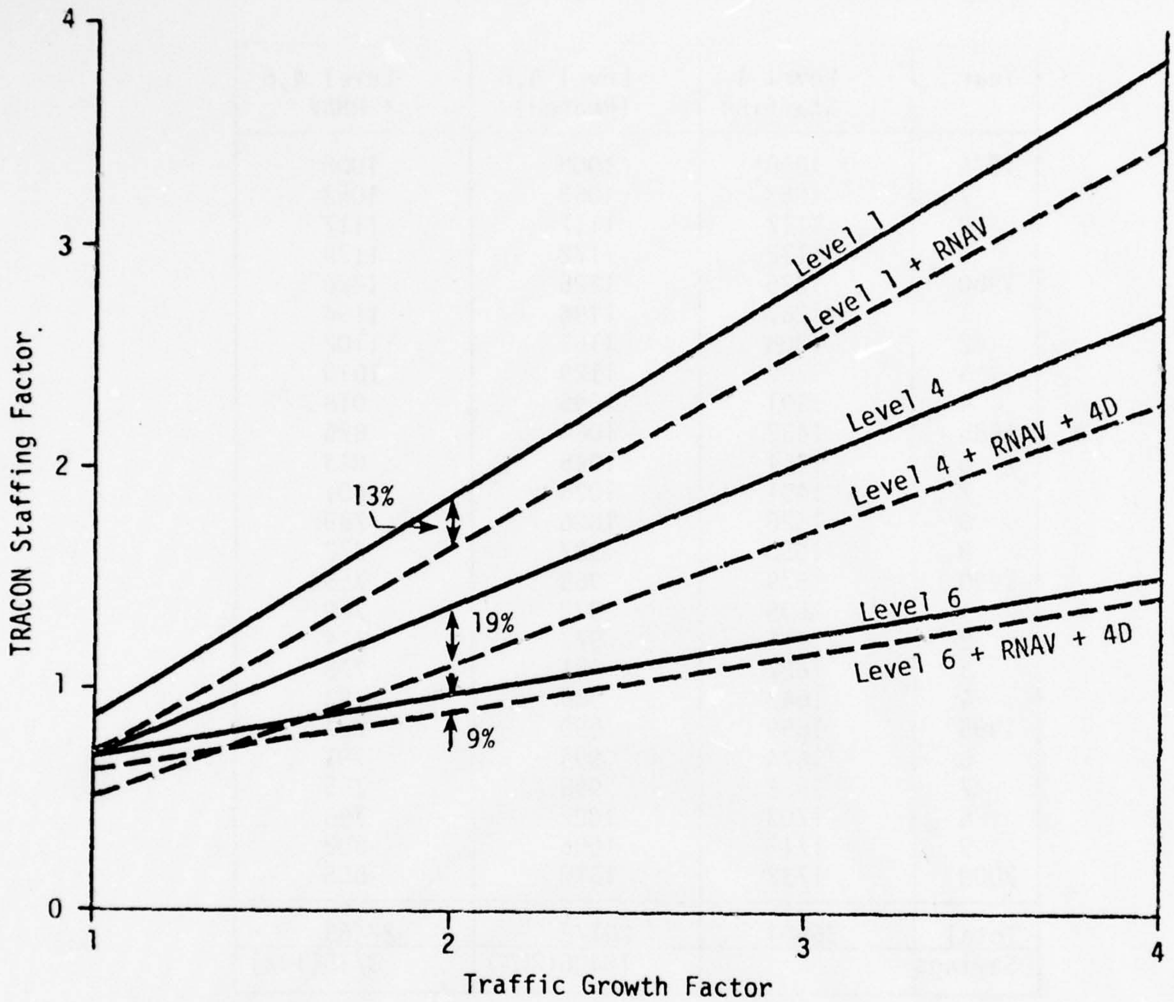


Figure 1.1 Linearized Relations of Staffing to Growth Factor

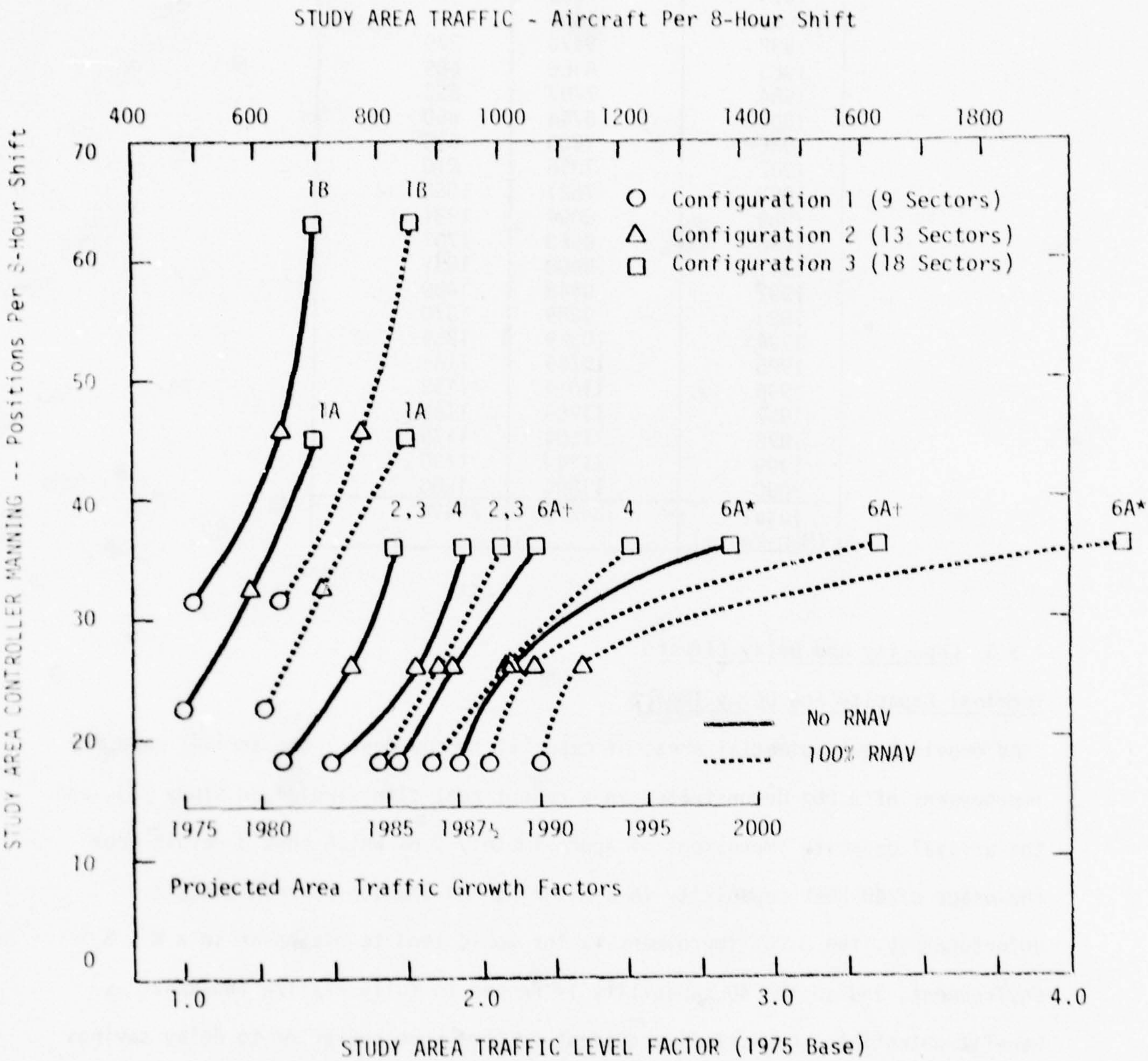
3.5 man case showed improved capacity in the level 1 (NAS Stage A) case, whereas added staffing had no capacity effect on enhancement levels 2 through 6. The level 6B case (1.0 man sectors) is not shown since the resulting capacity is insufficient to meet projected demand. On this figure the traffic level factors for several future years are notated. Given this data, the staff requirement savings given the phased implementation of RNAV may be computed. By utilizing national growth projections, the staffing growth projection may be extrapolated

Table 1.5 RNAV Impact at Twenty-eight TRACONS

Year	Level 1 Staffing	Level 4,6 (Phased)	Level 4,6 + RNAV
1976	1008*	1008	1008
7	1063	1063	1063
8	1117	1117	1117
9	1172	1172	1172
1980	1226	1226	1226
1	1267	1194	1194
2	1308	1161	1102
3	1350	1129	1010
4	1391	1096	918
1985	1432	1064	825
6	1461	1045	813
7	1491	1026	801
8	1520	1006	789
9	1550	987	777
1990	1579	968	765
1	1595	972	769
2	1611	977	774
3	1627	981	778
4	1643	986	783
1995	1659	990	787
6	1674	994	791
7	1688	998	795
8	1703	1002	798
9	1717	1006	802
2000	1732	1010	806
Total	36584	26178	22463
Savings		10406(28%)	3715(14%)

*Adjusted Using Extrapolation Relationship

to all 20 centers resulting in the national controller staffing RNAV impact data stated in Table 1.6. This table shows a total 19 year staff requirement savings of 20,498 man years, or 11.1%. This is equivalent to a salary and benefits savings of $508 million. Only active controller staff have been considered. Inclusion of other demand-sensitive non-controller staff positions would increase staff savings by another 11 percent of the 20,498 man years indicated.



*100% data link aircraft
+50% data link aircraft

Figure 1.2 Study Area Manning Requirements as Affected by RNAV

Table 1.6 National ARTCC RNAV Staffing Requirements Impact

Year	Baseline Staffing	RNAV Savings
1975	7656	—
1980	11059	—
1982	9476	379
1983	8466	689
1984	7707	653
1985	6744	450
1986	7000	630
1987	7256	810
1988	7621	1060
1989	8094	1381
1990	8568	1702
1991	9008	1591
1992	9448	1480
1993	9889	1370
1994	10329	1259
1995	10769	1148
1996	11014	1158
1997	11259	1169
1998	11504	1179
1999	11749	1190
2000	11994	1200
Total (Man-Years)	185279	20498

1.3.3 Capacity and Delay Effects

Terminal Capacity and Delay Impact

RNAV provides two potential areas of capacity improvement: the arrival capacity improvement of 3.26% demonstrated in a recent real time simulation study [9], and the arrival capacity improvment of approximately 4.6% which should result from the usage of 4D RNAV capability in a Metering and Spacing environment [1]. Unfortunately, the 3.26% improvment factor would tend to disappear in a M & S environment, and so the 4D capability is needed to fully realize the RNAV benefit potential. Capacity improvement factors were converted to delay savings on a daily basis for twenty-nine high delay airports. The phased RNAV implementation scenario stated earlier was applied to these airports to derive annual fuel and time cost savings based upon the projected mixes of aircraft types at each airport. These savings are stated in terms of millions of pounds

of fuel and cost of fuel (given a range of fuel prices) and aircraft DOC cost, given a range of time-sensitive DOC cost parameter assumptions (discussed in Section 3.1.2). These results are given in Table 1.7.

The total fuel saving over the 19 year period RNAV should be in use amounts to 3.77 billion gallons of fuel saved due to delay reductions. The significance of this is highlighted by comparing it to total air carrier fuel consumption for 1975, which was 7.28 billion gallons (from CAB data). The total 19 year fuel and time cost savings ranges from $2.5 billion to $4.2 billion, depending upon the cost assumption used.

Table 1.7 Annual Fuel and Time Delay Savings

YEAR	FUEL SAVINGS (millions of lbs)	TIME COST SAVINGS LOW $*	TIME COST SAVINGS HIGH $*	TOTAL
1982	94.	$ 6.2M	$ 10.9M	
'83	293.	19.3	34.2	
'84	592.	39.6	78.3	
'85	876.	58.9	103.4	
'86	1413.	95.2	167.4	
'87	1394.	93.9	165.5	
'88	1356.	91.3	161.5	
'89	1301.	87.6	155.3	
1990	1227.	82.7	146.8	
'91	1290.	86.7	154.3	
'92	1353.	90.7	161.9	
'93	1416.	94.7	169.4	
'94	1479.	98.7	176.9	
'95	1542.	102.7	184.4	
'96	1594.	105.8	190.5	
'97	1646.	108.8	196.5	
'98	1698.	111.9	202.5	
'99	1750.	114.9	208.6	
2000	1802.	118.0	214.6	
LOW $ TOTAL*	$ 904.M	$1608M		$2512M
HIGH $ TOTAL*	1358.M		$2883M	4241M

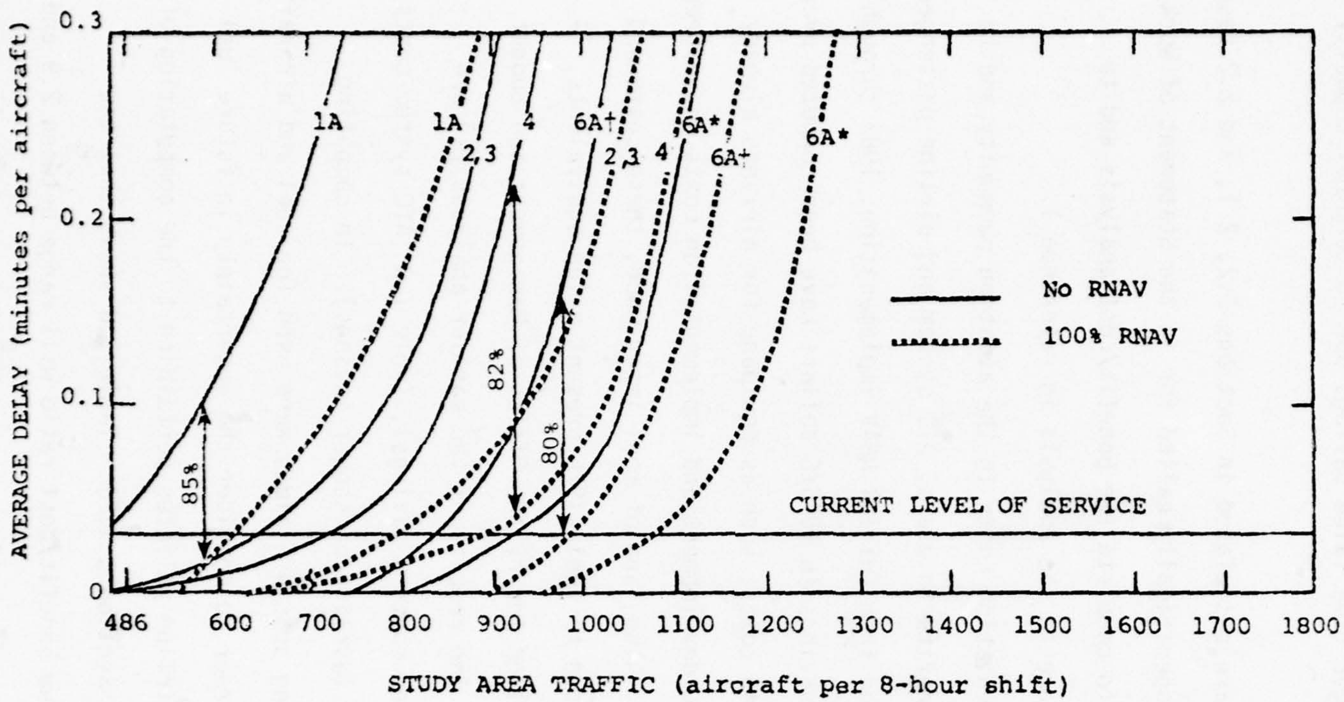
*Refers to the low and high fuel/time cost assumptions discussed in Section 3.1.2.

Enroute Capacity Impact

There was no source of enroute delay savings identified at this time as being caused by RNAV which can be considered independently of controller staffing requirements. The RNAV-induced sector capacity improvements were interpreted in terms of reductions in controller staffing requirements given that a constant level of service (enroute delay) should be maintained. However, Section 3.3 contains an analysis of the potential of RNAV to reduce enroute delays given that the controller staffing level is constrained, rather than being allowed to expand to provide service equivalent to present standards. If the staffing level were constrained, delays would rise significantly as traffic demand increases. This trend is illustrated by the curves in Figure 1.3, which relate mean delay per aircraft to traffic demand. An individual curve is shown for each enhancement level (1,2 & 3,4, 6A-50% data link equipped, and 6A-100% data link equipped), and for each enhancement level plus RNAV. As before, level 6B was not included due to insufficient capacity. The degree of RNAV savings for three potential situations is illustrated by the three vertical lines on the plot. Savings on the order of 80% of delays experienced are typical for the three cases illustrated.

1.3.4 Present Value Benefit/Cost Analysis

Comprehensive estimates of all major RNAV implementation cost and benefit (cost savings) categories were formulated in an earlier study and are reported in detail in reference 1. The only major implementation cost or benefit category not included was an evaluation of general aviation benefits. This was deferred due to the complexity involved in accurately estimating GA benefits due to the diversity of GA operations. A product of the present study has been to update three important benefit calculations, resulting from the more intensive analyses conducted:



*100% data link aircraft
†50% data link aircraft

Figure 1.3 Typical RNAV Enroute Delay Savings Examples

- Airline delay savings due to terminal capacity improvements
- ATC controller staff growth savings
- Airline passenger time value savings due to terminal capacity improvements

The first two of the above are calculated in Sections 3.2, 2.1, and 2.2 respectively. The third was not specifically called for in the Statement of Work, but was performed in order to complete the benefit/cost analysis and to provide a comprehensive update to the analysis in reference 1.

The analysis of implementation costs to the aviation community and to the ATC system, and RNAV benefits to users, ATC system and airline passengers was performed over the period from initial RNAV implemenation, 1982 through 2000. Totals of costs and savings in 1975/6 dollars have been computed over the 19 year period. (Certain costs, such as equipage for airlines already equipped, and RNAV procedure development and implementation costs, have been computed starting in 1976.) Also, and of most importance, these costs and benefits have all been reduced to their 1976 present value equivalents. A discount rate of 10%, as called for by the Office of Management and Budget [10], was used throughout. The results of the earlier analyses [1] are summarized in Table 1.8 (user costs & savings), Table 1.9 (ATC system costs and savings) and Table 1.10 (airline passenger savings). In computing airline savings, two bounding sets of values were used for fuel and aircraft incremental time costs in order to consider the uncertainty in future fuel prices and differences in airline policies pertaining to the computation of incremental time costs (see Section 3.1.2). Table 1.8 shows that the overall airline present value benefit/cost ratio will range between 2.9 and 5.0, which are quite large ratios. Also, they understate the overall payoff

Table 1.8 User Costs and Savings Through the Year 2000 [1]

Cost or Savings Source	Total Dollars	1976 Present Value	Cost* Assumption
Airline Equipage Costs (incl. maintenance)	$ 1436 M	$ 442 M	
GA Equipage Costs (incl. maintenance)	345 M	95 M	
Airline Terminal (2D) RNAV Savings	$ 1627 M 2738 M	$ 371 M 622 M	(Low) (High)
Airline Enroute (2D) RNAV Savings	1919 M 3259 M	425 M 718 M	(Low) (High)
Airline VNAV (3D) RNAV Savings	447 M 726 M	105 M 170 M	(Low) (High)
Airline Capacity (4D) RNAV Savings	1832 M 3118 M	401 M 683 M	(Low) (High)
Total Airline Savings	$ 5825 M 9841 M	$ 1302 M 2193 M	(Low) (High)
Airline Present Value Benefit/Cost Ratio		2.9 5.0	(Low) (High)

*Refers to the usage of two sets of operating cost interpretations.

to an individual aircraft over a fixed system lifetime, since these figures included purchases of systems for new aircraft at ever accelerating rates through the year 2000. The ATC system benefit/cost ratio, 9.9, is shown in Table 1.9. This is, of course, an extremely large payoff figure. Table 1.10 gives the airline passenger benefits data, but no ratio since the passengers incur no explicit cost due to RNAV.

Table 1.11 provides an overall benefit/cost assessment, including general aviation costs and airline passenger benefits. The resulting benefit/cost ratio will range from 5.5 to 7.1, indicating the large overall relative benefit of RNAV.

Table 1.9 ATC System Costs and Savings Through the Year 2000 [1]

Cost or Savings Source	Total Dollars	1976 Present Value
RNAV Implementation Costs	$ 19.8 M	$ 12.9 M
Enroute VORTAC Costs	2.4 M	0.8 M
Total ATC System Costs	$ 22.2 M	$ 13.8 M
Terminal Area VOR Savings	$ 36.1 M	$ 8.0 M
Terminal Controller Staff Savings	26.4 M	8.0 M
Enroute Controller Staff Savings	422.0 M	120.7 M
Total ATC System Savings	$ 484.5 M	$ 136.7 M
ATC Present Value Benefit/Cost Ratio		9.9

Table 1.10 Airline Passenger Benefits Through the Year 2000 [1] $12/Passenger Hour

Savings Source	Total Dollars	1976 Present Value
Passenger Time Value - Terminal (2D)	$ 1910 M	$ 434 M
Passenger Time Value - Enroute (2D)	2205 M	487 M
Passenger Time Value - VNAV (3D)	492 M	115 M
Passenger Time Value - Capacity (4D)	2455 M	538 M
Total Passenger Time Savings	$ 7062 M	$ 1574 M

In Table 1.12, the revisions made in this study are summarized. The terminal area capacity impact, now including the RNAV 3.26% arrival capacity effect and a recalculated 4D effect, gives airline delay savings benefits of $2512 million (low costs) to $4241 million (high costs), an increase of approximately 36% over the earlier calculation (Table 1.8). Terminal controller staff savings amount to $92 million, as opposed to $26.4 million derived earlier, an increase of more than three times. This is due largely to the fact that RNAV productivity impact was larger than was previously expected, and did not drop very much when DABS/CMA was introduced. The enroute controller staff savings, $508 million, is only 20% more than the earlier estimate. Passenger time value savings due to terminal capacity improvements increased 36% to $3329 million, as it should since it is caused by the same savings factors which induced the airline delay savings discussed above. Revised totals for airline savings, ATC savings and passenger savings, as well as revised present value benefit/cost ratios, are also stated in Table 1.12.

A revised overall RNAV benefit/cost assessment is presented in Table 1.13. The low-cost-assumption benefit/cost ratio is increased from 5.5 to 6.2, and the high-cost-assumption benefit/cost ratio is increased from 7.1 to 8.0, reflecting even more emphatically the overall beneficial nature of the RNAV feature of UG3RD.

Table 1.11 Previous Overall RNAV Benefit/Cost Assessment as Derived in Reference 1

1976 Present Values

	Low Cost Assumption	High Cost Assumption
Present Value Air Carrier Benefits	$ 1302 M	$ 193 M
Present Value ATC System Benefits	137 M	137 M
Present Value Passenger Benefits	1574 M	1574 M
Total Present Value Benefits	$ 3013 M	$ 3904 M
Present Value Air Carrier Costs	$ 442 M	$ 442 M
Present Value GA Costs	95 M	95 M
Present Value ATC System Costs	14 M	14 M
Total Present Value Costs	$ 551 M	$ 551 M
Benefit/Cost Ratio	5.5	7.1

Table 1.12 Savings Data Revised in This Study

	Total Dollars	1976 Present Value	Cost Assumption
Airline Capacity (RNAV + 4D) Savings	$ 2512 M 4241 M	$ 570 M 962 M	(Low) (High
Terminal Controller Staff Savings	92 M	24 M	
Enroute Controller Staff Savings	508 M	121 M	
Passenger Time Value-Capacity (RNAV + 4D)	3329 M	753 M	
Total Airline Savings	$ 6505 M 10964 M	$ 1471 M 2472 M	(Low) (High)
Airline Present Value Benefit/Cost Ratio		3.3 5.6	(Low) (High
Total ATC System Savings	$ 636 M	$ 153 M	
ATC Present Value Benefit/Cost Ratio		11.1	
Total Passenger Time Savings	$ 7936 M	$ 1789 M	

Table 1.13 Revised Overall RNAV Benefit/Cost Assessment

1976 Present Values

	Low Cost Assumption	High Cost Assumption
Present Value Air Carrier Benefits	$ 1471 M	$ 2472 M
Present Value ATC System Benefits	153 M	153 M
Present Value Passenger Benefits	1789 M	1789 M
Total Present Value Benefits	$ 3413 M	$ 4414 M
Total Present Value Costs	$ 551 M	$ 551 M
Benefit/Cost Ratio	6.2	8.0

2.0 WORKLOAD AND PRODUCTIVITY IMPACT

2.1 TERMINAL CONTROLLER PRODUCTIVITY STUDY

The evaluation of the parameters which affect terminal controller workload has been the subject of study by several researchers for a number of years. Even the definition of the term "controller productivity" has evolved slowly as the factors which contribute to or detract from productivity have become better understood. Many of these studies have directly addressed the issue of RNAV impact on terminal workload and productivity, although to date these studies have been incomplete either in method of analysis, in the data collected (or collectable), or in terms of the assumptions concerning the effects of RNAV on the controller's tasks. Some (by no means all) of these studies are reviewed briefly below, leading up to the data sources which were used directly in this study in evaluating workload and productivity effects. These analyses are then presented in detail in Section 2.1.1 and 2.1.2. The results of the productivity analysis are projected for the major terminal areas over the time period of UG3RD program implementation, to the year 2000, in Section 2.1.3.

One of the first really comprehensive analyses of terminal operations and controller workload was a pair of internal FAA studies reported in reference 11, published in 1970. The first study analytically evaluated the effects of proposed physical and ATC improvements to the New York Terminal Area, while the second used real time simulation in order to evaluate the same improvements. The two studies, which produced comparable results, included an evaluation of RNAV terminal routes, andso were used as the data source in a 1972 analysis of probable controller productivity impact [3]. This data also formed the basis for productivity benefit projections in later reports [12, 2 and 1]. Other researchers have evaluated potential productivity improvements due to automation

enhancements and other aspects of UG3RD programs, including reference 13 (1971), and more recently references 14 and 15. The most comprehensive effort to analyze controller workload and productivity has been a continuing model development effort conducted by SRI, under the sponsorship of FAA. This effort has concentrated on analyzing the controller's tasks in detail in an effort to account for all of the activities of a control sector team and the time that each activity consumes. The first model development effort culminated in a three volume report [6]. It has been used subsequently by other researchers. In particular, the ARTS III enhancements benefit/cost study [16]controller productivity analysis was based upon the methodology reported in reference 6. More recent SRI reports [4, 8] have expanded the methodology to the point where it is sufficiently complete to serve as the basis for studies of many ATC system improvements or changes. In reference 4 the several major elements of the UG3RD program are evaluated in terms of their impact on workload and staffing requirements. This is very useful to the present study of RNAV impact for two reasons. First of all a valid, detailed methodology for assessing controller workload and staffing requirements is available so that the effects of an RNAV environment on those factors may be analyzed. Second, the fact that the several UG3RD program elements have been evaluated in that report presents a baseline for the evaluation of RNAV impact not only at present, but throughout the entire UG3RD implementation timetable.

The primary sources of controller workload data specific to RNAV are from the real time simulations of terminal operations performed at NAFEC. While the one mentioned earlier [11] was the original real time simulation to specifically test the inclusion of RNAV capabilities, it was not designed to isolate the particular effect of RNAV alone. Two simulations have been conducted

since that time using the NAFEC Digital Simulation Facility (DSF) which were specifically designed to test the impact of RNAV on terminal area operations [17, 9]. The experiments were designed to keep all other controllable variables constant while runs were made with varying percentage mixes of RNAV and conventional traffic. Great care was taken in the design of the simulations to exclude extraneous variables. This is particularly true of the more recent simulation [9]. For example, in order to compare radar vector traffic and RNAV traffic on an equivalent basis, the radar vector traffic were guided over the same nominal paths that the RNAV traffic navigated, in order to make the "distance traveled" measurement unbiased. In order to maintain unbiased measures of control actions per aircraft, and time and distance measures per aircraft, a set of "key" flights was designated which consisted of a large number of flights starting after the simulated environment was well supplied with traffic. By expressing these measures on a "key flight" basis, several normal sources of randomness were eliminated. Also, in order to eliminate the bias of a controller "learning curve" with respect to the use of RNAV control techniques, RNAV traffic mix assignments and controller subject team assignments were made in a randomized fashion in both simulation studies. The simulation was designed to represent operations at a high density airport under conditions where the capabilities of the controller were tested at the saturation point, whereas in the earlier simulation [20], traffic levels per controller were not as high. This was obtained by simulating a modified New York JFK environment, where a second independent arrival runway was added, but where no additional control sectors were furnished to service the added traffic. This allowed RNAV impacts to be measured under the stress of a full workload situation. While many of the results of both of the recent NAFEC simulations are quite

similar, the more recent one will be used in this workload study because of the improvements to experiment design and data collection methods discussed above.

In the sections which follow, the two basic data sources used in this study are introduced in detail. These are the Oakland Bay TRACON controller workload and productivity analysis performed by SRI [4], and the recent New York real time simulation performed at NAFEC [9]. In Sections 2.1.1 and 2.1.2 these studies are explored and the RNAV impact methodology is developed and applied to the San Francisco terminal area (Oakland Bay TRACON). In Section 2.1.3 the San Francisco results are generalized and projected over twenty-nine major terminal areas through to the year 2000.

2.1.1 Terminal Workload and Capacity Impact Analysis

Workload and Capacity Analysis Framework

This analysis of terminal controller workload and control sector traffic capacity is based on the methodologies developed at SRI over several years, as reported in the Oakland Bay TRACON study, reference 4. The analysis technique, which concerned San Francisco operations in that particular report, considers that controller work or tasks are assignable to three categories:

- Routine work
- Surveillance work
- Conflict processing work

The methodology is applied to compute the amount of time expended by a control sector team in each work category per aircraft handled. Workload could be computed for each sector team member, but usually only the radar controller position is of interest since its workload limits the capacity of the sector. The radar controller performs all surveillance work and conflict processing work. Surveillance work is that amount of time spent routinely scanning and

monitoring each flight. Conflict processing work per aircraft is related to the airspace geometry of concern and the density of traffic in the area.

The amount of routine work that a controller performs is dependent upon the staffing assignments of the sector. The SRI technique breaks down routine work into five categories:

- A/G Communications (A/G Comm)
- Data Entry/Display Operation (DED)
- Flight Strip Processing (FSP)
- Interphone Communications (I/P Comm)
- Face-to-Face Communications (F-F Comm)

The radar man performs all A/G Communications, while the breakdown of the remaining categories as defined by SRI is shown in Table 2.1. Where one-half of a coordinator is

Table 2.1 Sector Position Task Assignments

Sector Staffing	Positions Manned	Task Assignments				
		A/G Comm	DED	FSP	I/P Comm	F-F Comm
1	Radar	Yes	Yes	Yes	Yes	None
1.5	Radar	Yes	Yes	Most	No	Yes
	½ Coordinator	No	No	Some	Yes	Yes
2	Radar	Yes	Some	Most	No	Yes
	Handoff	No	Most	Some	Yes	Yes
2.5	Radar	Yes	No	Most	No	Yes
	Handoff ½ Coordinator	No	Yes	Some	Yes	Yes

shown, he is shared with another sector. In addition to this staffing, one or more flight data positions may be required in a TRACON.

The methodology is applied to determine what the traffic capacity of a given sector is under the traffic circumstances that it serves. The sector capacity is calculated for each staffing level, e.g. 1, 1.5, 2 and 2.5 positions. Required staffing level is therefore known for serving any specific level of traffic.

Traffic capacity of a sector is defined as the maximum level of traffic where total radar controller task time reaches a certain threshold. The SRI analyses have determined this level to be 48 minutes of task performance out of each hour [6]. Total task time is determined by first computing surveillance time, which is directly related to the length of time a given aircraft is under the control of a sector. To this is added the conflict processing time, which is computed given the route geometry in the sector and the traffic densities along the routes. Crossing, overtake, merging and parallel approach coordination conflict types are considered separately (the details of all of these computations will be introduced later). Routine workload for the radar control position is computed from a highly detailed breakdown of controller tasks. Each individual task has been quantified as to the length of time required for its performance (which doesn't change generally from terminal area to terminal area, or based on which control position performs it), and the frequency of occurrence per aircraft handled. The frequency of occurrence can be highly dependent upon the particular control sector of interest, and on the individual terminal area. The resulting tables of task event freqencies and performance times were developed from observational data taken at terminal areas, as reported in references 4, 6 and 8. Total routine task performance time is thus computed by summing the products of the individual event frequencies and performance times.

This controller workload methodology is very adaptable to solving problems related to the workload and capacity impacts of various ATC automation features and other ATC system developments. Reference 4 is such an evaluation which analyzed control sector workload and capacity given various levels of ATC system enhancements. These levels are listed in Table 2.2. Since they encompass all of the UG3RD features which will impact controller productivity, they will,

Table 2.2 ATC Enhancement Levels Evaluated in Reference 4

Level	ATC Enhancement
1	Basic ARTS III Capability
2	Add Automatic Flight Data Handling (FDH)
3	Add Metering & Spacing (M&S)
4	Add Conflict Probe
5	Add RNAV
6	Add DABS, Control Message Automation (CMA)

with certain modifications, serve as the basis for this study of RNAV impact on controller productivity as the UG3RD features are implemented. The most significant modification will be the elimination of level 5, which considers RNAV as a separate, definitive stage which occurs after the first four levels. It is replaced by an evaluation of the impact of RNAV on each of the remaining five levels, so that a time-phased RNAV implementation environment may be assessed, as is done in Section 2.1.2.

At this point it is appropriate to define the terms "sector capacity" and "controller productivity". An ATC sector has reached its capacity when the radar controller workload level reaches the maximum practical point, defined as 48 minutes per hour in reference 4. Note that sector capacity and controller workload per aircraft handled at some traffic density less than capacity are not inversely proportional, as is so often assumed. While most controller time is indeed directly proportional to traffic level, conflict processing workload is proportional to the square of the traffic level. Therefore, capacity is defined as a quadratic rather than linear function. As a result, ATC enhancements which reduce conflict potential often result in a seemingly disproportionate improvement to sector capacity. Also, as control positions are added to a sector, offloading some workload from the radar man, sector capacity is increased, although the improvement is less than proportional since conflict processing tasks are not offloaded.

Controller productivity is directly related to sector capacity. Abstractly it is the ability of an individual to handle traffic. Therefore, average productivity at capacity is the capacity of a sector divided by the number of members of the sector team. As a result, while adding positions to a sector may be the only means available to create needed capacity in a given situation, it can markedly reduce mean individual controller productivity.

Basic Workload Analysis Methodology

Routine Work:

The investigations reported in references 4, 6, 8 and others have resulted in Tables 2.3 through 2.7, which represent routine workload for the basic ARTS III case (Level 1) at San Francisco. Table 2.3 shows the routine event frequency estimates for each of the two final sectors, two feeder sectors and two departure sectors at San Francisco. These values are average frequencies per aircraft handled by each sector. Tables 2.4 through 2.7 list the routine event performance times for each type event, per event, for the radar control position. The four tables present the situations for the several team sizes, 1 through 2.5 positions per sector, respectively.

Total routine work times per aircraft handled may be computed simply by multiplying the appropriate column tabulations together (frequency times time per event gives total time) and summing the result. The results of this process are presented in Tables 2.8 and 2.9. The effects of added control positions on R-controller routine workload may be clearly seen.

Surveillance Work:

The surveillance task workload relationship is analyzed in reference 4. It was found that each aircraft under a sector's control was scanned approximately once per minute, and each scan requires 1.25 seconds. Therefore, the workload per aircraft is dependent upon the length of time it is under the jurisdiction of a given control sector, called the average sector transit time. These results are presented in Table 2.10. In general, these do not

Table 2.3
ROUTINE EVENT FREQUENCY ESTIMATES
OAKLAND BAY TRACON

Routine Control Event Description		Event Frequency by Sector (event/aircraft)					
Event Function	Basic Event and Supplemental Event	AR-1 Woodside Final	AR-2 Foster Final	AR-9 South Feeder	AR-10 North Feeder	DR-1 Sutro Departure	DR-2 Richmond Departure
Control jurisdiction transfer	Handoff acceptance	1.00	1.00	1.00	0.96	0.80	0.79
	Manual acceptance-silent	1.00	1.00	1.00	0.96	0	0
	Tower departure call	0	0	0	0	0.80	0.79
	Controller coordination	0.08	0.13	0.13	0.05	0.10	0.11
	Handoff initiation-silent	0	0	1.00	1.00	1.00	1.00
	Controller coordination	0	0	0	0.09	0.30	0.21
Traffic structuring	Initial pilot call-in	1.00	1.00	1.00	1.00	1.00	1.00
	TCA clearance request	0	0	0	0.04	0.20	0.21
	Initial controller response	1.00	1.00	1.00	1.00	1.00	1.00
	Altitude instruction	0.33	0.13	0.94	0.68	0.40	0.21
	Data update	0	0	0.50	0.23	0.20	0.21
	Heading/route instruction	0.92	0.33	0.94	0.86	0.10	0.21
	Speed instruction	0	0.07	0.63	0	0	0
	Approach/runway advisory	0.92	0.27	0.94	0.86	0.05	0.05
	PVD display update	0	0	0.94	0.86	0.05	0.05
	Traffic advisory	0.08	0.20	0	0	0.10	0.05
	ATIS advisory	0.08	0.07	0.13	0.14	0.10	0.11
	Altimeter setting advisory	0	0	0	0	0.30	0.21
	Transponder code assignment	0	0	0	0.04	0.20	0.21
	Controller coordination	0	0	0.07	0	0.20	0
	Altitude instruction	1.17	0.87	0.13	0.73	0.25	0.79
	Data update	0	0	0.13	0.14	0.10	0.21
	Controller coordination	0	0	0	0	0.05	0.05
	Heading/route instruction	0.33	0.13	0	0.45	0.50	0.95
	Controller coordination	0	0	0	0	0.10	0
	Speed instruction	0	0.20	0.25	0.09	0	0
	Approach clearance	1.08	0.93	0	0	0	0.05
	Runway assignment	0.33	0.53	0.13	0.05	0.15	0.11
	Traffic advisory	1.17	1.00	0.19	0.18	0.55	0.89
	Pilot altitude report	0.08	0.20	0.19	0.09	0.45	0.84
	Pilot heading/position report	0.08	0	0	0	0.10	0.16
	Pilot speed report	0.17	0	0	0.09	0.05	0
	Miscellaneous A/C communication	0	0	0.07	0.09	0.15	0.26
	Frequency change	1.00	1.00	1.00	1.00	1.00	1.00
	Transponder code change	0	0	0	0	0.10	0.11
	Approach/runway advisory	0.58	0.60	0.13	0.09	0	0
Pilot request	Altitude revision	0	0	0.19	0.05	0.15	0.11
	Controller coordination	0	0	0.06	0	0	0.05
	Route/heading revision	0	0	0	0	0.20	0.21
	Controller coordination	0	0	0	0	0.05	0.11
	Miscellaneous pilot request	0.17	0.20	0.13	0.05	0	0.26
General intersector coordination	Pointout acceptance	0.17	0.13	0.06	0	0.15	0.26
	Pointout initiation	0	0	0.25	0	0.50	0.42
	Control instruction approval	0	0	0.06	0.09	0.25	0.37
	Planning advisory	0.17	0	0.06	0.09	0.15	0.05
	Aircraft status advisory	0.25	0.07	0.13	0.18	0.25	0.11
General system operation	Data block forcing/removal	0.67	0.53	0.50	0.96	0.20	0.84
	PVD display adjustment	0.25	0	0.19	0.18	0	0.05

Table 2.4
R-CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1, 1-MAN TEAM

Routine Control Event Description		Performance Time by Task (min-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance			2			2
	Manual acceptance-silent		2				2
	Tower departure call				2		2
	Controller coordination				6		6
	Handoff initiation-silent		3				3
	Controller coordination				6		6
Traffic structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4	10	6			20
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3	2			8
	Controller coordination				5		5
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination				5		5
	Heading/route instruction	5					5
	Controller coordination				5		5
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6		2			8
	Controller coordination				5		5
	Route/heading revision	8		2			10
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3		6		9
	Pointout initiation				6		6
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 2.5
R-CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1, 1.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent		2				2
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent		3				3
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4	10	6			20
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3	2			5
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3			3	6
	Pointout initiation					3	3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 2.6
R-CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1, 2-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communi-cation	Data Entry/Display Operation	Flight Strip Process-ing	Inter-phone Communi-cation	Face-to-Face Communi-cation	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4		6			10
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3		2			5
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					4
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance					3	3
	Pointout initiation					3	3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

Table 2.7
R-CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 1, 2.5-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/ Display Operation	Flight Strip Processing	Inter-phone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination					3	3
	Handoff initiation-silent						0
	Controller coordination					3	3
Traffic structuring	Initial pilot call-in	4		1			5
	TCA clearance request	4		6			10
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update			2			2
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update						0
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3					5
	Controller coordination					3	3
	Altitude instruction	5					5
	Data update			2			2
	Controller coordination					3	3
	Heading/route instruction	5					5
	Controller coordination					3	3
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change	4		1			5
	Transponder code change	2					2
	Approach/runway advisory	3					4
Pilot request	Altitude revision	6		2			8
	Controller coordination					3	3
	Route/heading revision	8		2			10
	Controller coordination					3	3
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance					3	3
	Pointout initiation					3	3
	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory						0
General system operation	Data block forcing/removal						0
	PVD display adjustment						0

change as the automation enhancements (Levels 2, 3, 4 and 6) are added, since they do not affect the surveillance required or the average transit time.

Table 2.8 Routine R-Controller Work Times Per Aircraft Handled(Seconds/Aircraft)
Basic ARTS III Capability (Level 1)
Woodside Final Sector

Team Size	A/G Comm.	DED	FSP	I/P Comm.	F-F Comm	Total
1 Man	42.88	5.27	4.00	3.60	0.00	55.75
1.5 Man	42.88	5.27	2.00	0.00	1.26	51.41
2 Man	42.88	2.76	2.00	0.00	1.26	48.90
2.5 Man	42.88	-0-	2.00	0.00	1.26	46.14

Table 2.9 Routine R-Controller Work Times per Aircraft Handled (SFO)
Basic ARTS III Capability (Level 1)

Team Size	Final		Feeder		Departure	
	Woodside	Foster	South	North	Sutro	Richmond
1 Man	55.75	46.33	48.10	47.38	54.70	65.76
1.5 Man	51.41	43.20	43.63	43.18	45.50	57.79
2 Man	48.90	40.81	38.45	37.74	39.45	51.28
2.5 Man	46.14	39.22	33.56	31.74	38.70	48.46

Table 2.10 Controller Surveillance Work per Aircraft Handled (SFO)

Sector	Average Transit Time (min.)	Surveillance Work per Aircraft (sec.)
Woodside Final	5	6.25
Foster Final	5	6.25
South Feeder	4	5.00
North Feeder	3	3.75
Sutro Departure	5	6.25
Richmond Departure	4	5.00

Conflict Processing Work:

In reference 4 relationships are derived which relate the potential for conflict situations (called conflict event frequency factor) to route geometry. The units of the conflict frequency factor are

$$(\text{Conflicts/Hr})/(\text{Operations Rate})^2$$

which means that conflict rate is proportional to the square of aircraft operations rate. The conflict frequency factors for SFO are tabulated in

Table 2.11 for IFR conditions. In order to determine the per aircraft workload, however, two additional factors must be known: the traffic density, and resolution time per conflict. If overall workload is to be evaluated at a given level of

Table 2.11 Conflict Event Frequencies (SFO) Basic ARTS III Capability

Sector	Conflict Event Frequency Factor			
	Crossing	Merging	Overtaking	Coord. Appr. Merging
Woodside Final	0	0	.0130	0
Foster Final	0	.0032	.0212	0
South Feeder	0	.0046	.0028	.0038
North Feeder	.0015	.0033	.0074	.0038
Sutro Dep.	.0057	.0007	.0023	0
Richmond Dep.	.0045	0	.0008	0

traffic, then traffic density is known. If capacity is to be calculated, then a quadratic expression must be solved.

In reference 4 the conflict resolution times have been estimated for each conflict category. To make these estimates, the conflict event process was broken down into two parts, conlict detection and assessment, and conflict resolution. Furthermore, the coordinated approach merge conflict involves coordination (this conflict category was required because the parallel approach runways at SFO are not independent during IFR conditions, and so coordination is required to prevent approach conflicts). The times required for each part of the conflict event process are listed in Table 2.12. Note that the coordinated approach merge conflict is affected by the presence of a coordinator, whereas other conflict types are handled entirely by the radar controller. Also, the approach merge conflict resolution time per aircraft is one-half of the 15 seconds required since only one of the two controllers involved will actually resolve the conflict.

Table 2.12 R-Controller Conflict Event Performance Times (Sec.)

Basic ARTS III Capability

Conflict Type	Sector Staffing	Detection & Assessment	Coordination	Resolution	Total
Crossing	All	20	0	20	40
Merging	All	20	0	15	35
Overtaking	All	20	0	10	30
Coord. Appr.	1 or 2 man	20	5	7.5	32.5
Coord. Appr.	1.5 or 2.5 man	10	3	7.5	20.5

Overall Workload Computation:

This section will present an example calculation of workload, capacity and productivity for the basic ARTS III case (Level 1) at SFO using the data presented above. The first step is to calculate conflict workload factors for each sector. The workload factor is the coefficient which will give workload (seconds) per aircraft handled when multiplied by operations rate "R" through that sector. Thus, total seconds of workload per aircraft can only be computed when the operations rate for the sector is specified. Table 2.13 lists these factors, and totals for each sector, where "R" stands for operations rate.

Table 2.13 SFO Sector Conflict Workload Factors (R-Controller)

Basic ARTS III Capability

Sector	Staffing	Conflict Workload Factors (IFR)				
		Crossing	Merging	Overtaking	Coord. Appr.	Total
Woodside F.	All	0	0	.390R	0	.390R
Foster F.	All	0	.112R	.636R	0	.748R
South Feed	1 or 2 Man	0	.161R	.084R	.124R	.369R
South Feed.	1.5 or 2.5 Man	0	.161R	.084R	.078R	.323R
North Feed.	1 or 2 Man	.060R	.116R	.222R	.124R	.522R
North Feed.	1.5 or 2.5Man	.060R	.116R	.222R	.078R	.476R
Sutro Dep.	All	.228R	.025R	.069R	0	.322R
Richmond Dep.	All	.180R	0	.024R	0	.204R

Table 2.14 gives the actual calculation for radar controller workload for each sector. A nominal operations rate for each sector was derived in reference 4 at the 90 percentile peak hour values from operations data recorded at SFO for

FY1975. Since surveillance workload does not change as staffing is increased, it is listed separately at the top of the table. Routine workload data is taken from Table 2.9. Conflict event workload is computed by multiplying the values in Table 2.13 by the nominal operations rate at the top of Table 2.14. The three workload contributors for each case are summed to yield total workload per aircraft.

Table 2.14 SFO Sector Nominal R-Controller Workload
(seconds per aircraft handled)

Basic ARTS III Capability

	Woodside F.	Foster F.	South Feed.	North Feed.	Sutro D.	Richmond D.
Surveillance Wkld	6.25	6.25	5.00	3.75	6.25	5.00
Nominal Ops. Rate	27	20	18	26	23	38
1 Man Team:						
Routine Wkld	55.75	46.33	48.10	47.38	54.70	65.76
Conflict Wkld	10.53	14.96	6.64	13.57	7.41	7.75
Total per Aircraft	72.53	67.54	59.74	64.70	68.36	78.51
Per Hour (Min)	32.64	22.51	17.92	28.04	26.20	49.72
1.5 Man Team:						
Routine Wkld	51.41	43.20	43.63	43.18	45.50	57.79
Conflict Wkld	10.53	14.96	5.81	12.38	7.41	7.75
Total per Aircraft	68.19	64.41	54.44	59.31	59.16	70.54
Per Hour (Min)	30.69	21.47	16.33	25.70	22.68	44.68
2 Man Team:						
Routine Wkld	48.90	40.81	38.45	37.74	39.45	51.28
Conflict Wkld	10.53	14.96	6.64	13.57	7.41	7.75
Total per Aircraft	65.68	62.02	50.09	55.06	53.11	64.03
Per Hour (Min)	29.56	20.67	15.03	23.86	20.36	40.55
2.5 Man Team:						
Routine Wkld	46.14	39.22	33.56	31.74	38.70	48.46
Conflict Wkld	10.53	14.96	5.81	12.38	7.41	7.75
Total per Aircraft	62.92	60.43	44.37	47.87	52.36	61.21
Per Hour (Min)	28.31	20.14	13.31	20.74	20.07	38.77

These values are multiplied by nominal operations rate to produce R-controller workload per hour, in minutes. As may be seen these vary widely from sector to sector, showing that workload is not at all *uniform*, but depends on demand and other factors. These values are plotted as a function of sector staffing level in Figure 2.1. It shows the general slight downward trend of R-controller workload as sector staffing increases.

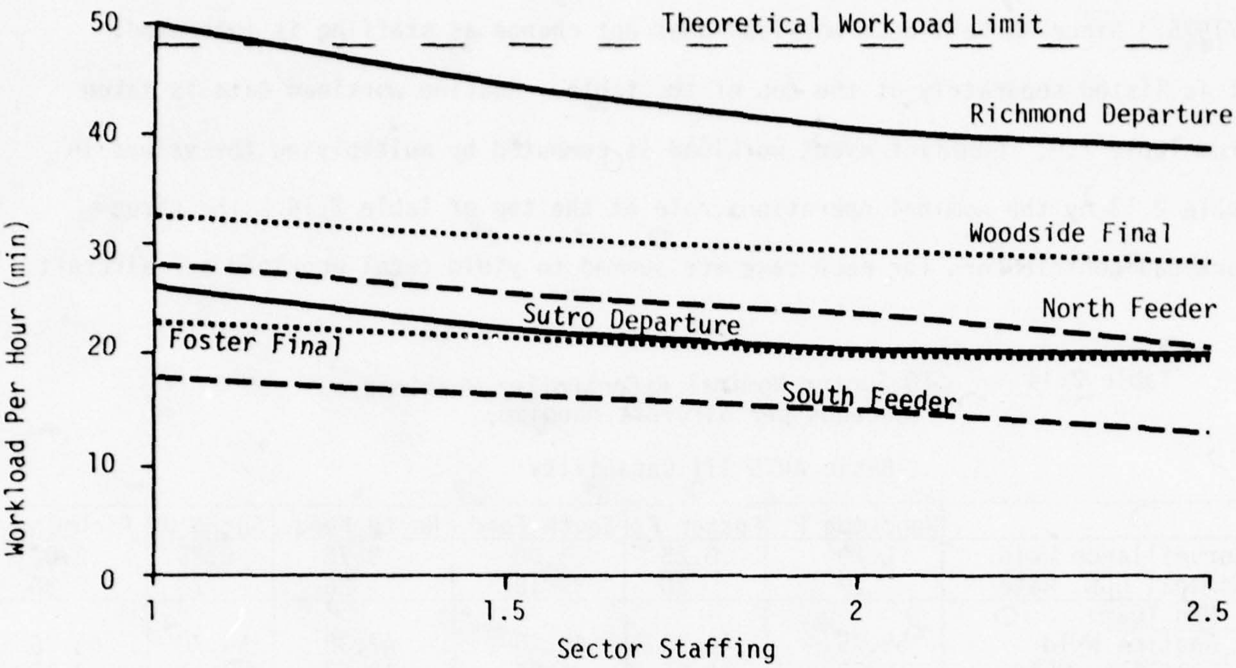


Figure 2.1 R-Controller Workload at Nominal Operations Rate (SFO)

Further computations have been made in order to calculate sector capacity and productivity as a function of sector staffing level. In Table 2.15 the data necessary for these calculations, and the results, are presented. The items necessary are the non-conflict workload totals per aircraft (routine plus surveillance), the conflict workload factor, and the total workload limit of 48 minutes per hour. By solving a quadratic equation, the level of demand which would induce 48 minutes per hour of workload can be derived. By definition, this is sector capacity. It is interesting to note that capacity does not differ greatly from sector to sector (from a low of 36.17 to a high of 41.99, i.e. 16%) while the nominal operations rate demands on these sectors varied widely. Also, as sector staffing increases, capacity increases somewhat, as expected. These capacity results are plotted in Figure 2.2, which shows that final sector

capacity increases the least rapidly. This is due largely to the fact that final controller workload is dominated by A/G communications (see Table 2.8), which are not relieved by the added sector positons, while with the other sectors other task types form almost 50% of the workload.

Table 2.15 SFO Sector Capacity and Productivity at Capacity

Basic ARTS III Capability

	Woodside F.	Foster F.	South Feed.	North Feed.	Sutro D.	Richmond D.
Nominal Ops Rate	27	20	18	26	23	38
1 Man Team:						
Non-Conflict Wkld	62.00	52.58	53.10	51.13	60.95	70.76
Conflict Rate	.390R	.748R	.369R	.522R	.322R	.204R
Capacity	37.57	36.17	41.99	40.00	39.15	36.80
Productivity at Capacity	1.39	1.81	2.33	1.54	1.70	0.97
1.5 Man Team:						
Non-Conflict Wkld	57.66	49.45	48.63	46.93	51.75	62.79
Conflict Rate	.390R	.748R	.323R	.476R	.322R	.204R
Capacity	39.43	37.25	45.48	42.79	43.75	40.43
Productivity at Capacity	0.97	1.24	1.68	1.10	1.27	0.71
2 Man Team:						
Non-Conflict Wkld	55.15	47.06	43.45	41.49	45.70	56.28
Conflict Rate	.390R	.748R	.369R	.522R	.322R	.204R
Capacity	40.58	38.11	47.29	44.50	47.27	44.12
Productivity at Capacity	0.75	0.95	1.31	0.86	1.03	0.58
2.5 Man Team:						
Non-Conflict Wkld	52.39	45.47	38.56	35.49	44.95	53.46
Conflict Rate	.390R	.748R	.323R	.476R	.322R	.204R
Capacity	41.90	38.70	52.02	48.98	47.74	45.85
Productivity at Capacity	0.62	0.77	1.16	0.75	0.83	0.48

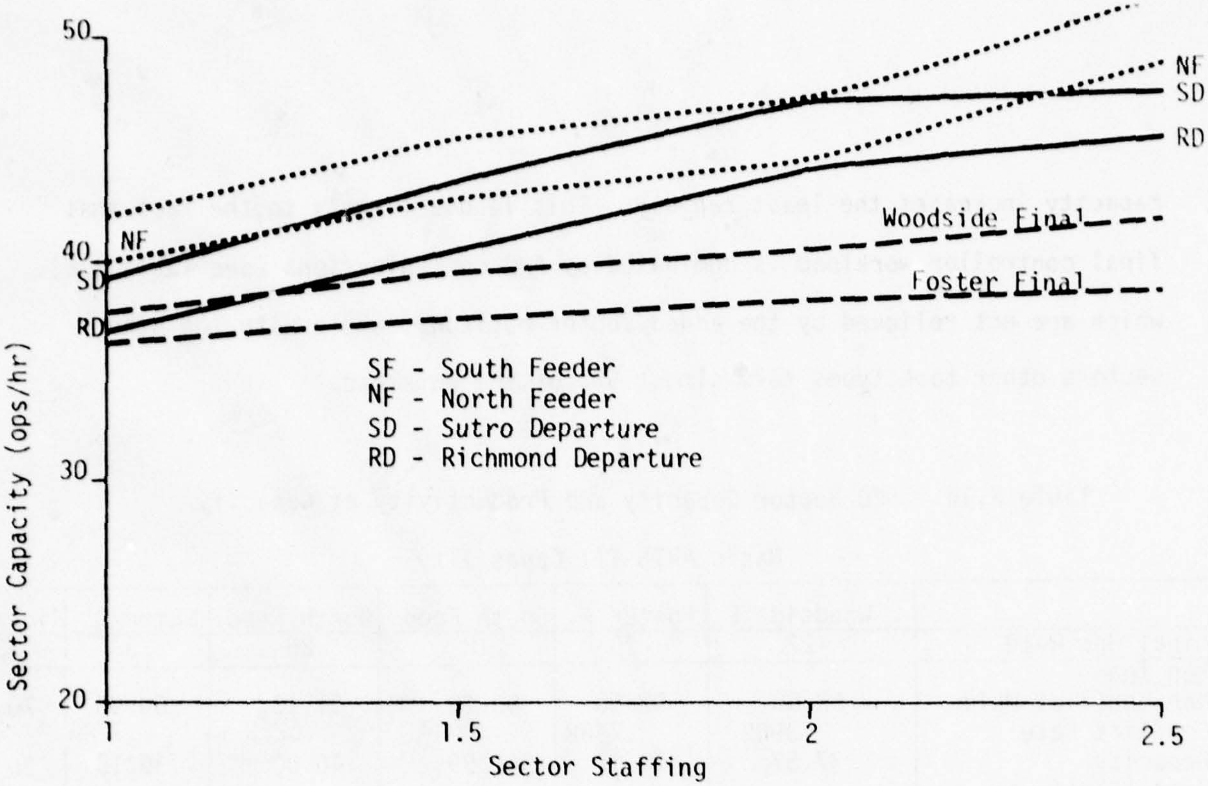


Figure 2.2 Control Sector Capacity (SFO)

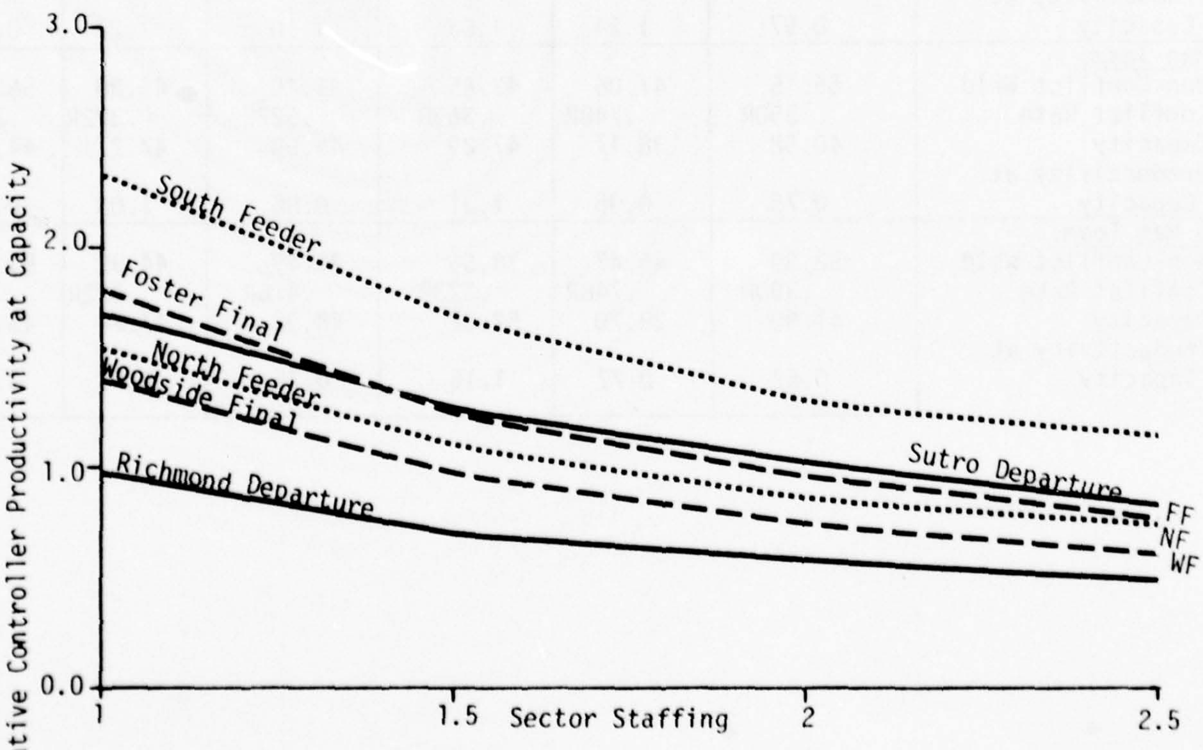


Figure 2.3 Controller Productivity at Capacity, Relative to Nominal Operations Rate (SFO)

Also in Table 2.15 relative productivity is calculated. Here productivity is computed given that demand equals capacity. Productivity is defined here relative to current (1975) productivity at the nominal operations rate, and includes the number of controllers manning the sector. These results are plotted in Figure 2.3, which shows the strong downward trend of average productivity as sector staffing is increased.

Treatment of ATC Enhancements in Reference 4

In reference 4 five levels of ATC enhancements beyond the basic ARTS III capability, as listed in Table 2.2, are analyzed in an effort to determine the impact on workload and sector capacity. The logic applied for each level are reviewed here, and any exceptions taken in this analysis are noted.

Level 2, Automatic Flight Data Handling

Automatic Flight Data Handling (FDH) will provide electronic tabular displays of flight data eliminating the need for flight data strips in routine operations. The net effect on radar controller activities is to totally eliminate flight strip processing tasks, to somewhat reduce interphone communication tasks (eliminate tower departure handoff call and intersector pointout communications), but at the expense of some additional data entry and display operation tasks needed to update the FDH data base (handoff times are reduced, but altitude instructions, frequency changes, route or heading changes not in the flight plan, and intersector pointout initiations must be keyed in to update the data base). The net result is a significant reduction in R-controller task time per aircraft. The new event performance times for the R-controller are shown in Table 2.16 (1 man team; the reader is referred to Reference 6 for more detail). The workload impact is computed and presented later in this section. Conflict workload and surveillance workload are not affected by FDH.

Table 2.16
R-CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 2, 1-MAN TEAM

Routine Control Event Structure		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent		2				2
	Tower departure call						0
	Controller coordination				6		6
	Handoff initiation-silent		1				1
	Controller coordination				6		6
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2					2
	Altitude instruction	3					3
	Data update		3				3
	Heading/route instruction	3					3
	Speed instruction	3					3
	Approach/runway advisory	3					3
	PVD display update		3				3
	Traffic advisory	3					3
	ATIS advisory	3					3
	Altimeter setting advisory	3					3
	Transponder code assignment	3	3				6
	Controller coordination				5		5
	Altitude instruction	5					5
	Data update		3				3
	Controller coordination				5		5
	Heading/route instruction	5					5
	Controller coordination				5		5
	Speed instruction	5					5
	Approach clearance	6					6
	Runway assignment	5					5
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/C communication	5					5
	Frequency change	4	1				5
	Transponder code change	2					2
	Approach/runway advisory	3					3
Pilot request	Altitude revision	6	3				9
	Controller coordination				5		5
	Route/heading revision	8	3				11
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3				3
	Pointout initiation		3				3
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

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Level 3, Metering and Spacing

In the analysis of M & S impact on workload in reference 4, it is presumed that the M & S capability would provide cues to the R-controller which would reduce the effort required in identifying and resolving arrival conflicts. Routine workload and surveillance workload are presumed to not be affected by the M & S capability. The present analysis takes exception to these assumptions based upon detailed definitions of the M & S function in reference 18, and upon recent analyses of the M & S function as reported in reference 1. First of all, as presently conceived [18], Metering and Spacing automation will virtually eliminate airspace conflicts between arriving aircraft, and so will eliminate all local merge, overtake and coordinated approach merge conflicts on arrival and final approach routes. This is accomplished through prior planning and organization of the traffic by the M & S system. It would be programmed to avoid creating conflict situations. Therefore, in an M & S environment all feeder and final sector conflicts except crossing conflicts would be eliminated. Furthermore, in performing the spacing function, the M & S system would routinely issue vectoring commands for every arrival aircraft during high volume time periods. With reference to the analysis in reference 1, the same number of commands would ordinarily be issued for each aircraft handled. Based on the organization of traffic in SFO, it is presumed that the feeder sectors would routinely issue one heading vector and the final sectors would issue two. In addition, the final sectors would issue one speed command not associated with a heading command in most, but not all, cases as a final arrival time control technique (75% of final approach aircraft were assumed to receive such a command). The surveillance function was not judged to be affected by M & S. Based on these changes in methodology, the R-controller workload impact has

been recomputed for the M & S case, the results of which are presented later in this section.

Level 4, Conflict Probe

The automated conflict probe function was analyzed and determined to significantly affect the conflict event performance time estimates, but not conflict event frequencies or routine workload or surveillance workload. The conflict alert feature was also examined but, since it is only a last minute warning feature for avoiding conflicts which the controller has missed, it was not found to routinely impact any of the workload measures. The effect of the conflict probe on conflict event performance times is to drastically reduce the time required for conflict detection and assessment, in all cases from 20 seconds to 5 seconds except for coordinated approach merges, where the time is reduced from 10 seconds to 5 seconds. These new values would replace the values listed in Table 2.12.

Level 5, Area Navigation

The RNAV feature was evaluated in reference 4 as a separate enhancement to the UG3RD system. In this study, of course, RNAV will be evaluated as it would impact each stage of implementation of UG3RD individually, both for general interest and so that overall impact might be assessed for various UG3RD implementation schedules.

The assessment of RNAV capabilities in reference 4 concluded that the only effects of RNAV would be to allow overtake conflicts on departure routes to be eliminated. The logic applied was that multiple close-spaced parallel departure routes could be established, and so departure overtakes could be prevented by routinely alternating departure routes. No other impacts were identified in that study. Further analysis in the present study has shown

that there are several areas where RNAV will affect workload. These include not only conflicts, but routine tasks and surveillance tasks as well. Therefore, exception is taken to the findings of that study, based primarily upon the findings of the real time terminal simulation studies [17, 9], which have shown routine controller workload measures to be reduced significantly when dealing with RNAV-equipped aircraft. Furthermore, while parallel departure routings could be designed into terminal routings, they have not been in terminal area designs produced so far [19], and so are not included as a workload reducer in this analysis. The specific RNAV effects included are discussed later in this section.

Level 6, DABS & Control Message Automation

This level of automation enhancement comprises a major step forward in the reduction of controller workload. This facility was analyzed in reference 4, and many significant effects on routine tasks and overall routine and conflict workload were found. There are two primary impact areas with respect to the routine events performed and the task times associated with their performance. The numbers of air/ground communication tasks which must be performed are reduced very significantly through data link communications of many routine messages. The results derived are shown in Table 2.17, which should be compared with 2.16 for the non-data link case. Also, the data entry/display operation task category is strongly affected. Here a few tasks are eliminated (such as data entry of certain "initial controller response" items), but several more are added. In particular, many functions that do not require overt action on the part of the radar controller, but rather involve monitoring functions, have been added. This monitoring role is termed "operational cognizance" in that reference, and items falling in that category are marked with an asterisk in Table 2.17.

Table 2.17
R-CONTROLLER
ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
OAKLAND BAY TRACON, SYSTEM 6, 1-MAN TEAM

Routine Control Event Description		Performance Time by Task (man-sec/event)					
Event Function	Basic Event and Supplemental Event	A/G Communication	Data Entry/Display Operation	Flight Strip Processing	Interphone Communication	Face-to-Face Communication	Total
Control jurisdiction transfer	Handoff acceptance						0
	Manual acceptance-silent						0
	Tower departure call						0
	Controller coordination				6		6
	Handoff initiation-silent		1				1
	Controller coordination				6		6
Traffic structuring	Initial pilot call-in	4	1				5
	TCA clearance request	4	10				14
	Initial controller response	2	5*				7
	Altitude instruction						0
	Data update						0
	Heading/route instruction						0
	Speed instruction						0
	Approach/runway advisory						0
	PVD display update						0
	Traffic advisory	3					3
	ATIS advisory						0
	Altimeter setting advisory						0
	Transponder code assignment	3					3
	Controller coordination				5		5
	Altitude instruction		3*				3
	Data update						0
	Controller coordination	5	3		5		13
	Heading/route instruction		3*				3
	Controller coordination	5	3		5		13
	Speed instruction		3*				3
	Approach clearance		3*				3
	Runway assignment		3*				3
	Traffic advisory	5					5
	Pilot altitude report	5					5
	Pilot heading/position report	5					5
	Pilot speed report	5					5
	Miscellaneous A/G communication	5					5
	Frequency change		3*				3
	Transponder code change						0
	Approach/runway advisory						0
Pilot request	Altitude revision	6	3				9
	Controller coordination				5		5
	Route/heading revision	8	3				11
	Controller coordination				5		5
	Miscellaneous pilot request	6					6
General intersector coordination	Pointout acceptance		3*				3
	Pointout initiation		3*				3
	Control instruction approval				5		5
	Planning advisory				5		5
	Aircraft status advisory				5		5
General system operation	Data block forcing/removal		3				3
	PVD display adjustment		3				3

*Operational cognizance

The other area of DABS/CMA impact on workload involves conflict resolution workload. Surveillance workload was not affected. Conflict workload is reduced since the resolution commands are automatically generated and data linked. However, ten seconds of conflict resolution time is still assigned to the R-Controller for monitoring purposes. As a result, a total of fifteen man-seconds per conflict are required. The overall workload computations are presented later in this section.

Derivation of RNAV Impact on Workload

In this section data taken primarily from two sources (the most recent real time terminal simulation study [9] and the analysis of RNAV terminal area route designs [[illegible]]) will be analyzed in order to derive the impact to be expected due to RNAV on routine workload, conflict workload and surveillance workload.

The real time simulation showed that the usage of RNAV capability improves terminal operations in [illegible]. For example, the transition to a 100% RNAV environment showed the following improvements:

- Distance flown per arrival dropped by 3.1% (nominal radar vector and RNAV route lengths were identical).
- Distance flown per departure flight remained constant.
- Time in system (after handoff acceptance by the feeder controllers) for arrivals dropped by 6.3% (departure time in system remained constant).
- Start-point delay (holding time) for arrivals dropped by 34%.
- Arrival operations rate increased 3.2%.
- Total number of G/A radio contacts dropped by the following amounts:

Final	25.9%
Feeder	31.1%
Departure	56.2%

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The real time simulation showed that the usage of RNAV capability improves terminal operations in many ways. For example, the transition to a 100% RNAV environment showed the following improvements:

- Distance flown per arrival dropped by 3.1% (nominal radar vector and RNAV route lengths kept identical).
- Distance flown per departure flight remained constant.
- Time in system (after handoff acceptance by the feeder controllers) for arrivals dropped by 6.3% (departure time in system remained constant).
- Start-point delay (holding time) for arrivals dropped by 34.4%.
- Arrival operations rate increased 3.2%.
- Total number of G/A radio contacts dropped by the following amounts:

Final	25.9%
Feeder	31.1%
Departure	56.2%

- Total duration of G/A radio contacts dropped by the following amounts:

Final	28.5%
Feeder	36.5%
Departure	66.6%

- Total duration of G/A radio contacts per aircraft handled dropped by the following amounts:

Final	29.4%
Feeder	37.0%
Departure	67.1%

It is quite apparent from these statistics, and from the overall generally favorable response from the controllers used as subjects in the experiments, that RNAV improves operational efficiency and reduces controller workload. The difficult part of the task at hand is to be able to analyze this workload impact in a detailed sense, within the framework of the SRI analysis technique described in the previous section, so that the impact of RNAV as it interacts with the other UG3RD features may be determined, and so that the total workload impact (as opposed to merely the communications workload effects measured in the simulation study) may be assessed. The RNAV impact determination techniques for each workload category (routine, conflict processing, surveillance) are discussed in the following sections.

Routine Workload Impact

The NAFEC simulation study [9] measured overall controller ground/air communications time and message count for each control position (see the statistics above). This was done simply by recording the count and duration of which the microphone is keyed. However, this method does not record anything concerning the content of the messages, and so only the overall RNAV trend is

demonstrated by these statistics. The Digital Simulation Facility (DSF) at NAFEC is configured to record other information based upon the activities of the subject pilots taken in response to controller instructions. Thus, each time a subject pilot receives a route, speed, heading, RNAV offset or altitude command, or in cases of certain pilot reports as requested by ATC, these activities are recorded by virtue of the fact that the subject pilot enters the data in each case on a keyboard. This data is collected and statistically reduced at a later time. The problem with this data is, first of all, not all controller messages are so recorded, since only those directly affecting the route of flight, etc., are keyed in by the subject pilot. The second problem is that, since several such control actions could be communicated in a single message, there is no direct correspondence between message count and these control action counts. Thus, the control message count data cannot be used to directly complement the control actions count data in order to complete the detailed routine message workload effects analysis. As a result, while RNAV impact on most routine message categories has been measured not all have been measurable, and so zero impact is assumed for those.

An analysis of the control actions data in reference 9 has been performed by categorizing the control actions as follows:

- Lateral Control Activities (including radar vector heading command, RNAV parallel offset, cancel offset and direct to waypoint commands).
- Altitude instruction
- Speed instruction
- Pilot-initiated instructions

Analyses of each type of control sector (final, feeder, departure) have been performed by averaging the data for the two individual sectors in each case, e.g. the two final sectors, and presenting the results on a per aircraft handled basis.

This data is listed in Table 2.18 for the 0% and 100% RNAV participation cases. The results show very large reductions in lateral control (vectors, offsets, etc.) and altitude change instructions in every case. Lateral control actions are reduced due to self-navigation, and altitude messages are reduced due to the fact that the altitudes are a part of the published routes. Speed changes were essentially unaffected by RNAV, which is as expected. Pilot initiated control activities are reduced, probably due to the usage of published routings and altitudes.

Table 2.18 Control Action Count per Aircraft by Type of Action

Control Action Type	Final Sectors			Feeder Sectors			Departure Sectors		
(RNAV Participaton)	0%	100%	Δ	0%	100%	Δ	0%	100%	Δ
Lateral Control	2.539	1.022	-59.7%	1.574	0.458	-70.9%	3.157	0.470	-85.1%
Altitude Change	1.184	0.617	-47.9%	1.132	0.064	-94.3%	1.313	0.397	-69.8%
Speed Change	1.872	1.883	0.6%	1.141	1.147	0.5%	0.003	0.003	--
Pilot Initiated	2.250	1.484	-34.0%	0.010	0.028	18.0%*	3.108	1.023	-67.1%

*Because of small count values, this figure was presumed to be noise and set to zero.

The results of this analysis of the control action count data will be applied to the routine workload analysis for each level of ATC enhancement studied through the following procedure. Each of the routine A/G communications tasks identified by the analysis in reference 4, and noted in the "A/G Comm" column in Table 2.4, has been categorized into one of the four categories in Table 2.18, or a fifth category "Miscellaneous A/G Comm". The result of this categorization is shown in Table 2.19. The RNAV impact on routine A/G communications workload is then computed from the control event frequencies (Table 2.3) and A/G communication event performance times (such as Table 2.4, first column) for any case of enhancement level and sector staffing, where the resulting control function times are then summed in each of the five categories of Table 2.19, and reduced by the percentages shown in Table 2.18

Table 2.19 Categorization of Routine A/G Communication Events

Category	Event Types
Lateral Control	Initial response - Heading route instruction Heading/route instr.
Altitude Change	Initial response -- Altitude instr. Altitude instr.
Speed Change	Initial response -- Speed instr. Speed instr.
Pilot Initiated	Pilot Altitude report Pilot heading/position report Pilot speed report
Miscellaneous A/G	Initial pilot call-in Initial call-in -- TCA clearance request Initial controller response Initial response -- Approach/runway advisory -- Traffic advisory -- ATIS advisory -- Altimeter Setting -- Transponder code Approach clearance Runway assignment Traffic advisory Miscellaneous A/G Comm. Frequency Change Frequency Change -- Transponder Code -- Approach/runway advisory Altitude revision Route/heading revision Miscellaneous pilot request

(or left the same for the "miscellaneous" category). The results of such a process, for Level 1 (basic ARTS III) with 1 man sectors, is shown in Table 2.20. Here, as will be done throughout, the results for each pair of like sectors has been combined and averaged so as to better approximate a typical sector of that type.

Table 2.20 RNAV Impact on Routine A/G Communications Workload (Seconds/Aircraft)

Level 1, 1 Man Sectors

Control Action Type	Final		Feeder		Departure	
(RNAV Participation)	0%	100%	0%	100%	0%	100%
Lateral Control	3.03	1.22	3.83	1.11	4.09	0.61
Altitude Change	5.79	3.02	4.58	0.26	3.52	1.06
Speed Change	0.61	0.61	1.80	1.80	0	0
Pilot Initiated	1.33	0.88	0.93	0.93	4.00	1.32
Miscellaneous A/G	28.92	28.92	16.61	16.61	21.73	21.73
TOTAL	39.68	34.65	27.75	20.71	33.34	24.72
RNAV Δ		-12.7%		-25.4%		-25.9%

The remaining routine controller workload task categories of data entry/display operation (DED), flight strip processing (FSP), interphone communications (I/P Comm) and face-to-face communications (F-F Comm) consider controller routine activities which were not measured during the NAFEC real time simulation studies. As a result it was considered premature to attempt to estimate the probable RNAV impact on these categories. An examination of these functions shows that some are clearly not affected by RNAV, particularly those associated with routine intersector coordination, for example. However, some, such as FSP or I/P Comm activities directly associated with heading/route instructions and altitude instructions, could be beneficially affected. The values obtained for these categories are listed as "other routine" workload later in Table 2.23.

Conflict Processing Workload Impact

RNAV, through the facility of published self-navigated terminal routes, can be used to provide paths free of crossing conflicts in the terminal area. This is posible since a waypoint or let down fix can be located anywhere with an altitude (or altitude range) associated with it, thus providing separation from

crossing routes. This approach was used with great success in the extensive terminal area design work which has been performed to date [19]. Therefore, it is presumed for this study that, at an RNAV participation level of 100%, terminal area crossing conflicts are virtually eliminated.

There is no reason from a route design point of view why local merging, overtake, or coordinated approach merge conflicts would be eliminated due to RNAV. Specific route geometries may be optimized to reduce merge conflicts, but such minor effects have not been considered here. The other conflict aspect where RNAV can have an effect is on the times required for the processing of conflicts. Specifically, RNAV will not affect detection and assessment or coordination times, but will affect conflict resolution effort in some cases as discussed below. A table of RNAV conflict processing times used for this study appears as Table 2.21, which may be compared with Table 2.12.

Table 2.21 R-Controller Conflict Processing Times (Seconds)

Level 1 (Basic ARTS III)

Conflict Type	Operation	Conflict Processing Time					
		Detection & Assessment	Coordination	Resolution		Total	
				0%R	100%R	0%R	100%R
Crossing	Arrivals	20	0	20	N.A.	40	N.A.
	Departures	20	0	20	N.A.	40	N.A.
Local Merge	Arrivals	20	0	15	10	35	30
	Departures	20	0	15	4	35	24
Overtaking	Arrivals	20	0	10	10	30	30
	Departures	20	0	10	4	30	24
Coord. Appr. (1&2 Man Sectors)	Arrivals	20	5	7.5	5	32.5	30.0
Coord. Appr. (1.5&2.5 Man Sectors)	Arrivals	10	3	7.5	5	20.5	18.0

The values given in Table 2.21 for the 0% RNAV case are the same as those listed in Table 2.12. The reasons for the RNAV conflict processing time reductions in certain cases are as follows. In the crossing conflict case, an

RNAV resolution time is not given since there will be no such conflicts in an RNAV terminal environment. In the local merge conflict case for arriving aircraft, the conflict may be resolved with one (parallel offset) and sometimes two (offset followed by direct to) instructions. The NAFEC data shows that these instructions require less than four seconds, and so they are included at four seconds each. Two more seconds is assumed to be required for flight progress monitoring, yielding a total of ten seconds. In the departure case, the aircraft which must be offset to avoid the conflict may almost always be virtually ignored after the instruction is issued, since the departing aircraft may both be handed off to the center controller in that condition. Therefore, only four seconds is required for resolution. In the overtaking conflict case, speed control would usually be used for arrivals, making the RNAV situation identical to the vector situation. Concerning the departure situation, the faster aircraft may be assigned an offset, resulting in essentially the same situation as the departure merge conflict. The coordinated approach merge case is similar to the merge case for arrivals, i.e., at most two commands at four seconds plus two seconds for added monitoring. As in the radar vector case, the resolution times are halved for coordinated approach merges since only one of the two radar controllers involved would actually resolve the conflict. As before, total conflict processing workload per aircraft is computed by multiplying the conflict event frequencies in Table 2.11 by the resolution times in Table 2.21, summing the results for each sector and multiplying by traffic demand at that sector. The results for each pair of sectors have been averaged in the analysis to follow, to better represent a typical sector.

Surveillance Workload Impact

As stated previously, the overall surveillance workload required per aircraft was determined as the product of the one-minute scanning rate, the 1.25 second

scan time, and the time the aircraft is under that sector's jurisdiction. A review of the situation has not determined any reason why the scanning rate or scan time would be significantly affected due to RNAV. However, the real time simulation studies [17, 9] have shown (for arrivals), and the terminal area design study [19] has shown (for arrivals and departures) that RNAV significantly reduces the terminal route transit time, on the average. In the recent real time simulation study [9], time in system (not including holding time) was shown to be decreased by 6.3% for arrivals, and was unchanged for departures. The study of terminal route structures in reference 19 showed that route transit time at SFO drops by 10.0% for arrivals and by 4.8% for departures. These two sources of savings are independent and additive (approximately), since the latter represents route design effects while the former represents the controller's ability to manage the traffic. Therefore, the overall effects are 16.3% (arrival) and 4.8% (departure). Applying these values to the reference 4 data gives the results for surveillance workload shown in Table 2.22.

Table 2.22 RNAV Impact on Surveillance Workload

Sector	Transit Time		Workload/AC	
	0%R	100%R	0%R	100%R
Woodside Final	5	4.19	6.25	5.23
Foster Final	5	4.19	6.25	5.23
South Feeder	4	3.35	5.00	4.19
North Feeder	3	2.51	3.75	3.14
Sutro Departure	5	4.76	6.25	5.95
Richmond Departure	4	3.81	5.00	4.76

RNAV Workload Impact Computation

In this section the RNAV impact on radar controller workload is computed for each of the UG3RD enhancement levels studied. The case considered is the Oakland Bay TRACON, as before, with one-man sector team staffing assumed. In each analysis each pair of sectors has been combined and averaged to yield a more generally representative sector of each type. Controller workload in each case is evaluated at the traffic level determined to be the capacity of each type of sector for the Level 1, 0% RNAV case. In this way workload is related to the capacity of the baseline case rather than the historic traffic demand level used in Table 2.14 for the nominal workload computation.

Level 1, Basic ARTS III Capability

In Tables 2.20, 2.21 and 2.22 the results of the RNAV impact analysis for the Level 1 case were presented for the cases of routine, conflict and surveillance workload categories respectively. The results of the RNAV impact analysis on Level 1 are shown in Table 2.23. The first line, Total Communications per Aircraft, is taken directly from Table 2.20. The second line, Other Routine Workload, is that part which is not sensitive to RNAV, and consists of the DED, FSP, I/P Comm. and F-F Comm. categories. Listed are the averages for each pair of like sectors. An example tabulation of these routine components for the Foster Final sector is listed in Table 2.8. The third line lists surveillance workload, which is the sector pair average of the data in Table 2.22. The fourth line lists the IFR conflict workload factor. This is the sector pair average of the sums of the conflict factors for each type of conflict. Each conflict factor is the product of the conflict event frequency listed in Table 2.11 and the conflict processing time listed in Table 2.21. Conflict workload per air-

Table 2.23 RNAV Workload and Capacity Impact, Level 1 (Seconds/AC)

1 Man Team, Basic ARTS III Capability

TASK CATEGORY	FINAL		FEEDER		DEPARTURE	
	0% R	100% R	0% R	100% R	0% R	100% R
Total Comm.	39.68	34.65	27.75	20.71	33.34	24.72
Other Routine	11.38	11.38	19.71	19.71	26.90	26.90
Surveillance	6.25	5.23	4.38	3.66	5.63	5.36
IFR Conflict Rate	.569	.561	.445	.386	.263	.046
Nom. Capacity	37	37	41	41	38	38
Conflict Workload	21.05	20.76	18.25	15.83	9.99	1.75
TOTAL	78.36	72.02	70.09	59.91	75.86	58.73
RNAV Reduction		8.1%		14.5%		22.6%
CAPACITY	36.80	39.29	41.07	46.45	37.97	48.64
RNAV Increase		6.8%		13.1%		28.1%

craft is evaluated at the traffic level equal to the capacity of the baseline, non-RNAV system given in Table 2.23. This holds true in each of the following UG3RD enhancement analyses, so that the workload for each is related at the capacity of the present day system. These capacities are determined and shown in the last line of this table, and are rounded off for use in the line labeled "Nominal Capacity". The nominal capacity and conflict rate are multiplied to get conflict workload per aircraft. The routine, surveillance and conflict workload factors are summed on the "total" line. The percent reduction in workload is listed in the 100% RNAV columns. Sector capacity is computed from the quadratic relationship discussed earlier and presented in the "Capacity" line, with the RNAV increase listed in the 100% RNAV columns.

Ultimate capacity of the airport can of course be constrained by factors other than controller workload. For example, runway capacity can limit operations rate. Also, saturation of one sector (final, for example) can limit operations in other sectors. Therefore, it is not always possible that sector capacities will be achieved. In the New York real time simulation [9] which this analysis was based upon, runway capacity constraints were removed in order to saturate the controllers.

As is evident from Table 2.23, the final control sectors are least affected by RNAV capability. Workload there is reduced by 8%, while in the departure controller case workload is decreased by 23%, which is a very significant reduction. Potential capacity increases provided through the use of RNAV techniques are 7%, 13% and 28% for the Final, Feeder and Departure sectors, respectively. In Section 2.1.2, the impact which these capacity increases will have on sector staffing levels under conditions of rising traffic demand will be assessed. The remainder of this section is concerned with determining the effects of RNAV on workload and capacity for ARTS enhancement levels 2 through 6.

The primary effect of enhancement level 2 (automatic flight data handling) on controller tasks is to eliminate flight strip processing tasks, thereby reducing workload in the "other routine" category. None of the remaining categories (communications, surveillance and conflict processing) are disturbed. These effects were discussed in more detail earlier. The new values for "other routine" workload were computed as the sums of the products of the routine event frequencies listed in Table 2.3 for all headings except communications, and the event performance times listed in Table 2.16. Since no RNAV impact on the "other routine" category has been identified, the overall RNAV impact in the absolute sense for level two is the same as level one, although in percentage terms the impact is slightly greater. These results are tabulated in Table 2.24.

The level 3 enhancement, Metering & Spacing, is expected to affect both arrival conflict rates and routine communications workload. Departure workload should not be affected. The communications workload data were modified as follows: The values used for lateral control maneuvers (radar vector or parallel offset) were set to 10.00 seconds (two maneuvers) for the final sectors and 5.00 seconds for the feeder sectors. The values used for final sector speed

Table 2.24 RNAV Workload and Capacity Impact, Level 2 (Second/AC)

1 Man Team, Automatic Flight Data Handling

TASK CATEGORY	FINAL 0% R	FINAL 100% R	FEEDER 0% R	FEEDER 100% R	DEPARTURE 0% R	DEPARTURE 100% R
Total Comm.	39.68	34.65	27.75	20.71	33.34	24.72
Other Routine	8.48	8.48	15.65	15.65	18.17	18.17
Surveillance	6.25	5.23	4.38	3.66	5.63	5.36
IFR Conflict Rate	.569	.561	.445	.386	.263	.046
Nom. Capacity	37	37	41	41	38	38
Conflict Workload	21.05	20.76	18.25	15.83	9.99	1.75
TOTAL	75.46	69.12	66.03	55.85	67.13	50.00
RNAV Reduction		8.4%		15.4%		25.5%
CAPACITY	37.91	40.51	43.03	48.90	42.20	56.63
RNAV Increase		6.9%		13.6%		34.2%

control messages were set to 3.75 seconds (5.00 x 75% frequency). Furthermore, workload in these two categories remains the same in the 100% RNAV case since the same sequencing maneuvers must be performed regardless of RNAV capability according to the M&S techniques studied in reference 1. Otherwise, routine communications workload, other routine workload and surveillance workload are the same as for the level 2 case.

Conflict processing workload is significantly reduced for arrival aircraft by M&S since the M&S logic will prevent conflict situations from arising between arrival aircraft, as discussed earlier, but not necessarily between arrival aircraft and others. Thus the overtake, merge and coordinated approach merge conflict types are completely eliminated for arrivals. Referring to Table 2.11, which shows conflict event frequencies for the level 1 capability, it may be seen that neither final sector has any crossing conflicts. Therefore, under level 3, there will be no conflicts in the final sectors at all. Of the two feeder sectors, only one (north) has crossing conflicts, and frequency is low.

Therefore, feeder sector conflict rates are almost zero, as shown in the "IFR Conflict Rate" line of Table 2.25, which lists the overall workload and capacity impact results for the Metering and Spacing case.

As may be seen in Table 2.25, M&S reduces overall workload in comparison with level 2 significantly for the feeder and final sectors, and of course, there is no effect on the departure sectors. RNAV impact is not quite as great, since the lateral maneuver commands are not reduced by RNAV as they were for levels 1 and 2. However, the effect of RNAV is still quite significant. While the RNAV workload impact at nominal capacity is slightly reduced, the feeder and final sector capacity impacts are actually increased since conflicts are essentially eliminated.

Table 2.25 RNAV Workload and Capacity Impact, Level 3 (Seconds/AC)
1 Man Team, Metering and Spacing Capability

TASK CATEGORY	FINAL			FEEDER		DEPARTURE	
	0% R	100% R	4D	0% R	100% R	0% R	100% R
Total Comm.	49.79	46.57	42.82	31.62	25.39	33.34	24.72
Other Routine	8.48	8.48	8.48	15.65	15.65	18.17	18.17
Surveillance	6.25	5.23	5.23	4.38	3.66	5.63	5.36
IFR Conflict Rate	.000	.000	.000	.030	.000	.263	.046
Nom. Capacity	37	37	37	41	41	38	38
Conflict Workload	0	0	0	1.23	0	9.99	1.75
TOTAL	64.52	60.28	56.53	52.88	44.70	67.13	50.00
RNAV Reduction		6.6%	12.4%		15.5%		25.5%
CAPACITY	44.64	47.78	50.95	54.06	64.43	42.20	56.63
RNAV Increase		7.0%	14.1%		19.2%		34.2%

Since a Metering and Spacing environment was under study, the 4D RNAV (time control) effect on workload and capacity has been computed. The 4D effect qualified is the fact that the final speed reduction command would be eliminated (based on the analysis in reference 1). This saves an additional 3.75 seconds in routine communications workload. This resulted in a doubling of the percentage

workload and capacity improvements available from RNAV in the final sectors. This 4D impact is based on the analysis in reference 1, which presents an "evolutionary" 4D environment. Other 4D concepts may potentially shown even greater workload reduction.

The fourth enhancement level is the conflict probe function, which would serve to reduce controller conflict detection and assessment time. Conflict probe does not actually affect conflict event frequencies, but overall conflict workload is reduced due to the reduction in detection and assessment time to five seconds in every case. Table 2.26 presents the level 4 results. Since conflicts were virtually eliminated in the feeder and final sectors by M&S, only the departure sectors are significantly affected by conflict probe. The RNAV impacts on workload and productivity are comparable to the Metering and Spacing case.

Table 2.26 RNAV Workload and Capacity Impact, Level 4 (second/AC)

I Man Team, Conflict Probe Capability

TASK CATEGORY	FINAL 0% R	FINAL 100% R	FINAL 4D	FEEDER 0% R	FEEDER 100% R	DEPARTURE 0% R	DEPARTURE 100% R
Total Comm.	49.79	46.57	42.82	31.62	25.39	33.34	24.72
Other Routine	8.48	8.48	8.48	15.65	15.65	18.17	18.17
Surveillance	6.25	5.23	5.23	4.38	3.66	5.63	5.36
IFR Conflict Rate	.000	.000	.000	.019	.000	.158	.017
Nom. Capacity	37	37	37	41	41	38	38
Conflict Workload	0	0	0	0.78	0	6.00	0.65
TOTAL	64.52	60.28	56.53	52.43	44.70	63.14	48.90
RNAV Reduction		6.6%	12.4%		14.7%		22.6%
CAPACITY	44.64	47.78	50.95	54.66	64.43	44.84	58.48
RNAV Increase		7.0%	14.1%		17.9%		30.4%

In the sixth automation enhancement level, DABS and Control Message Automation produce significant changes to the workload environment and the RNAV impact on workload. As explained earlier, the DABS/CMA capability serves to drastically reduce routine communications workload, but with a corresponding (but lesser) increase in Data Entry & Display Operating workload. Also, conflict processing workload is reduced somewhat. Most of the increased DED workload is due to a one-for-one substitution of displayed control message data which must be absorbed by the controller for the A/G controller message so replaced by the DABS/CMA system. Since it is a one-for-one (displayed message-for-spoken message) substitution, where RNAV would have reduced the spoken message count, the DED function count is reduced instead. Therefore, many of the DED functions have been removed from the "other routine" category and combined with the "total communications" category. Since this amounts to a total recalculation of these categories, the calculation is presented in Table 2.27; it is based on Tables 2.3 and 2.17 and shows the separation of

Table 2.27 Controller Task Breakdown, Level 6

1 Man Team, DABS & CMA

CONTROL ACTION	FINAL		FEEDER		DEPARTURE	
	Comm.	DED	Comm.	DED	Comm.	DED
Lateral Control	0.00	6.00	0.00	3.00	0.00	2.33
Altitude Change	0.00	3.06	0.00	1.29	0.00	1.71
Speed Change	0.00	2.25	0.00	0.51	0.00	0.00
Pilot Initiated	1.33	0.00	0.93	0.00	4.00	0.00
Miscellaneous A/G	12.96	0.00	8.73	0.00	15.49	0.00
Other Routine	17.79		16.70		23.79	

tasks into the two types of workload. Note that the M&S workload per control message delivered is reduced from five to three seconds.

Conflict processing workload is reduced through DABS/CMA since conflict resolution time is reduced to ten seconds in each case. Therefore, conflict processing time totals fifteen seconds for all cases, since the conflict probe capability has already reduced detection and assessment time to five seconds per conflict.

The results of the DABS/CMA workload analysis are stated in Table 2.28, which shows that DABS/CMA significantly reduces sector workload in each type sector compared to the level 4 case. Correspondingly, the RNAV improvement in percentage terms has dropped somewhat, ranging from 6% to 21% as opposed to a range from 7% to 30% with level 4 conditions. However, this range still represents a very significant improvement to be expected to result from RNAV.

Table 2.28 RNAV Workload and Capacity Impact, Level 6 (seconds/AC)

1 Man Team, DABS & CMA

TASK CATEGORY	FINAL			FEEDER		DEPARTURE	
	0% R	100% R	4D	0% R	100% R	0% R	100% R
Total Comm. and DED	25.60	23.68	21.43	14.46	13.24	23.53	17.68
Other Routine	17.79	17.79	17.79	16.70	16.70	23.79	23.79
Surveillance	6.25	5.23	5.23	4.38	3.66	5.63	5.36
IFR Conflict Rate	.000	.000	.000	.011	.000	.105	.017
Nom. Capacity	37	37	37	41	41	38	38
Conflict Workload	0	0	0	0.45	0	3.99	0.65
TOTAL	49.64	46.70	44.45	35.99	33.60	56.94	47.48
RNAV Reduction		5.9%	10.5%		6.6%		16.6%
CAPACITY	58.02	61.67	64.79	79.10	85.71	49.53	60.18
RNAV Increase		6.3%	11.7%		8.4%		21.5%

Capacity Impact Summary

It is of significant interest at this point to review the control sector capacity results presented here, both in terms of the capacity effects of the four enhancement levels, and in terms of the capacity effects of RNAV on those levels. Capacity is of primary importance here since, as will be shown in the next section, capacity has direct implications with respect to staffing requirements.

In Figure 2.4 the capacity results are summarized using a bar chart format. Each sector type is shown separately. Sector capacity at 0% RNAV is shown with the dark bars, while sector capacity at 100% RNAV is indicated by the light bars. In addition, the capacity increment for the final approach sectors due to 4D with M&S is also shown. The same information is shown in a somewhat different manner in Figure 2.5. The top graph shows relative capacity of each sector type for each enhancement level without the influence of RNAV, while the lower graph presents the percent capacity improvement expected due to RNAV. From these figures it may be seen that the influence of the enhancement levels on departure sector capacity is only moderate, while the influence of RNAV on departure sector capacity is very significant. RNAV shows the least impact on the final approach sectors, although if the 4D contribution is included (as it probably will be), the effect is quite significant. The sector type most improved by the enhancement levels is the feeder type, since its workload is heavily dominated by routine communications tasks. This workload is substantially relieved by DABS/CMA.

2.1.2 Sector Staffing Implications of Capacity and Demand

In order to determine the controller staffing requirement, the relationship of sector capacity to sector staffing level must be defined. Then, given projected traffic demand growth data over a period of years, the required staffing for each sector may be calculated as a function of time. The calculations of sector

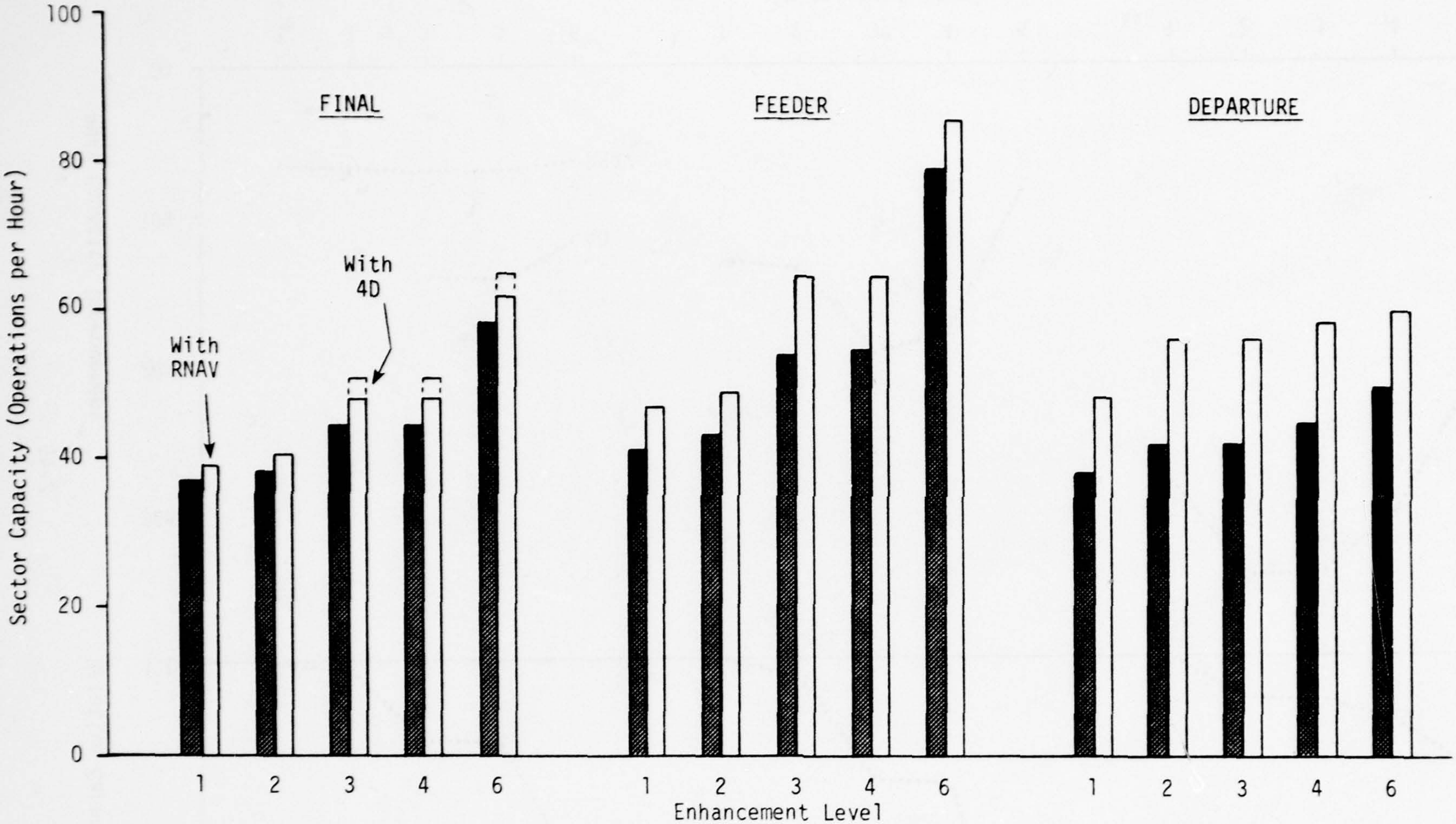

Figure 2.4 Control Sector Capacity of Each Enhancement Level (Cumulative)

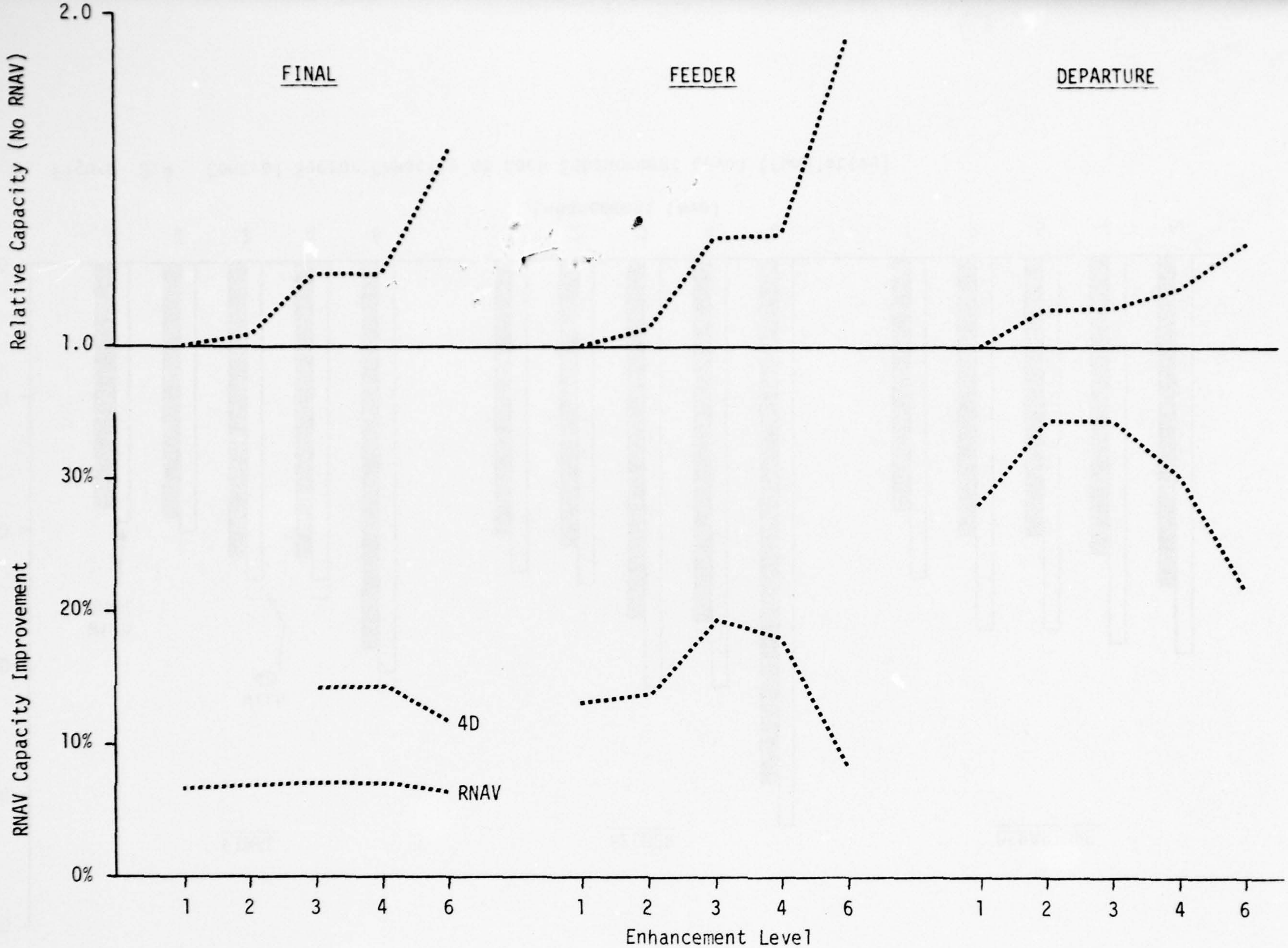

Figure 2.5 Control Sector Capacity Impact of Enhancement Levels (Cumulative) and RNAV

workload and capacity versus sector staffing were presented in Tables 2.14 and 2.15 for the level 1 (basic ARTS III capability without RNAV) case. Sector capacity results for the remaining enhancement levels with and without RNAV as a function of sector staffing are presented in this section. From these, overall TRACON radar room staffing projections are made as a function of traffic level.

The results of the capacity analysis are presented in Tables 2.29 a, b, and c for the final, feeder and departure cases respectively. Each case is different in terms of the effects which the enhancement levels, the use of RNAV, and increased sector staffing will have on sector capacity. Increasing staffing to 2.5 increases feeder and departure sector capacities by 23%, while it only increases final sector capacity by 9%. For the most part, the RNAV capacity improvement in percentage terms is not diluted by the enhancement levels except for level 6 (DABS/CMA), which has varying effects. Final sector capacity impact is only slightly reduced, while the feeder sector capacity impact diminishes 50%.

The next task is to reduce the five enhancements levels to a tractable number through appropriate combinations, and compute the actual TRACON controller staff level required for each combination as a function of the relative increase in traffic over a period of years. Expression of these results relative to a time-phased enhancement level implementation schedule and applying the projected traffic increases for SFO will result in an evaluation of required SFO staffing with no enhancements, with enhancements as scheduled, and with RNAV over and above that.

In a recent study of the influence of UG3RD features on controller staffing [7], which is based on the analysis in reference 8, the enhancement features are grouped conveniently and assigned a realistic implementation schedule. This study considered that the basic ARTS III system (level 1) will serve as is until 1980, whereupon several enhancements equivalent to levels 2, 3 and 4 are phased into full operational status by 1985. DABS/CMA, or level 6, is then phased into full

Table 2.29a Sector Capacity Summary ---- Final Sectors

ENHANCEMENT LEVEL	STAFFING	0 % RNAV				100% RNAV				RNAV & 4D			
		1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
1 (ARTS III)	Capacity RNAV Δ	36.8	38.2	39.2	40.1	39.3 6.8%	40.9 6.9%	42.0 7.0%	43.0 7.1%				
2 (AFDH)	Capacity RNAV Δ	37.9	38.4	39.2	40.1	40.5 6.9%	41.1 6.9%	42.0 7.0%	43.0 7.1%				
3 (M&S)	Capacity RNAV Δ	44.6	45.5	47.0	48.8	47.8 7.0%	48.8 7.2%	50.5 7.4%	52.5 7.7%	50.9 14.1%	52.1 14.5%	54.1 15.0%	56.4 15.6%
4 (CP)	Capacity RNAV Δ	44.6	45.5	47.0	48.8	47.8 7.0%	48.8 7.2%	50.5 7.4%	52.5 7.7%	50.9 14.1%	52.1 14.5%	54.1 15.0%	56.4 15.6%
6 (DABS/CMA)	Capacity RNAV Δ	58.0	59.6	62.6	—	61.7 6.3%	63.4 6.5%	66.9 6.8%	— —	64.8 11.7%	66.7 12.0%	70.6 12.7%	— —

Table 2.29b Sector Capacity Summary --- Feeder Sectors

ENHANCEMENT LEVEL	STAFFING	0 % RNAV				100% RNAV			
		1	1.5	2	2.5	1	1.5	2	2.5
1 (ARTS III)	Capacity RNAV Δ	41.1	44.1	45.8	50.4	46.4 13.1%	50.4 14.4%	52.4 14.4%	58.5 16.2%
2 (AFDH)	Capacity RNAV Δ	43.0	45.0	46.3	51.3	48.9 13.6%	51.5 14.6%	53.1 14.5%	59.7 16.4%
3 (M&S)	Capacity RNAV Δ	54.1	55.8	61.0	69.1	64.4 19.2%	66.9 20.0%	74.9 22.8%	88.2 27.6%
4 (CP)	Capacity RNAV Δ	54.7	56.4	61.8	70.4	64.4 17.9%	66.9 18.6%	74.9 21.1%	88.2 25.4%
6 (DABS/CMA)	Capacity RNAV Δ	79.1	82.7	93.7	—	85.7 8.4%	90.0 8.9%	103.7 10.7%	—

Table 2.29c Sector Capacity Summary --- Departure Sectors

ENHANCEMENT LEVEL	STAFFING	0 % RNAV				100% RNAV			
		1	1.5	2	2.5	1	1.5	2	2.5
1 (ARTS III)	Capacity RNAV Δ	38.0	42.1	45.7	46.8	48.6 28.1%	56.5 34.1%	63.9 39.9%	66.4 41.8%
2 (AFDH)	Capacity RNAV Δ	42.2	44.4	46.4	48.2	56.6 34.2%	61.2 37.8%	65.6 41.2%	69.7 44.5%
3 (M&S)	Capacity RNAV Δ	42.2	44.4	46.4	48.2	56.6 34.2%	61.2 37.8%	65.6 41.2%	69.7 44.5%
4 (CP)	Capacity RNAV Δ	44.8	47.5	49.9	52.1	58.5 30.4%	63.6 33.8%	68.5 37.1%	73.2 40.3%
6 (DABS/CMA)	Capacity RNAV Δ	49.5	52.3	57.2	—	60.2 21.5%	64.7 23.6%	72.5 26.9%	—

operational status by 1990. Since the enhancement levels considered here are cumulative (i.e., level 4 encompasses levels 1, 2 and 3), these three states are represented by level 1 (to 1980), level 4 (1985) and level 6 (1990). Therefore, we shall be further concerned only with those three levels. Since RNAV equippage is foreseen (for air carriers) to be phased in from 1982 to 1985 (as discussed in reference 1) the staffing impact of RNAV may be assessed by comparing an environment where RNAV is phased into full use by 1985 to an environment with no RNAV participation.

In order to illustrate the functional relationship between traffic growth and staffing by sectors, Tables 2.30a, b and c are presented which show staff assigned to each sector for several values of traffic growth ratio. These values for staffing are derived for a given growth ratio by multiplying the ratio by the 1974 peak day hourly operations listed in the table, and comparing the required capacity so derived with the available capacities stated in the appropriate entries in Table 2.29. Where the required capacity is less than the available capacity stated for a given staffing level, that value is the required staffing value. Where the required capacity exceeds all available capacities, the highest staffing value, 2.5 (2.0 for level 6), is assigned. In these cases it should be recognized that either operations rate will be limited, or resectorization and added controllers would be required to meet the stated operations rate.

The data presented in Table 2.30 are illustrated in more detail in graph form in Figures 2.6a, b and c. In these graphs the exact break points in traffic growth factor (rather than even increments of 0.25) are calculated and shown for greater accuracy. It should be emphasized that the fact that the curves level out as maximum sector staffing is reached means only that all the capacity increase available from this sector configuration has been realized, and that a new sector organization is required, along with more controllers, to serve the traffic indicated.

Table 2.30a SFO Staffing Versus Traffic Growth Ratio -- Level 1

NO RNAV	1974	TRAFFIC GROWTH RATIO								
Sector	OPS	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
Woodside Final	27	1.0	1.0	2.5	—	—	—	—	—	2.5
Foster Final	20	1.0	1.0	1.5*	1.5*	2.5	—	—	—	2.5
South Feeder	18	1.0	1.0	1.0	1.0	1.5*	1.5*	2.5*	2.5	2.5
North Feeder	26	1.0	1.0	1.0	2.0	2.5	—	—	—	2.5
Sutro Departure	23	1.5*	1.5*	1.5*	1.5	2.5	—	—	—	2.5
Richmond Departure	38	1.5	2.5	—	—	—	—	—	—	2.5
Subtotal		7	8	10	11	14	14	15	15	15
Flight Data		1	1	1	1	2	2	2	2	2
Total		8	9	11	12	16	16	17	17	17
Manning Factor		1.00	1.13	1.38	1.50	2.00	2.00	2.13	2.13	2.13

100% RNAV	1974	TRAFFIC GROWTH RATIO								
Sector	OPS	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
Woodside Final	27	1.0	1.0	1.5	2.5	—	—	—	—	2.5
Foster Final	20	1.0	1.0	1.5*	1.5*	1.5	2.5	—	—	2.5
South Feeder	18	1.0	1.0	1.0	1.0	1.0	1.5*	1.5*	1.5*	2.5
North Feeder	26	1.0	1.0	1.0	1.0	2.0	2.5	—	—	2.5
Sutro Departure	23	1.0	1.0	1.0	1.5*	1.5*	1.5	2.5*	2.5*	2.5
Richmond Departure	38	1.0	1.0	2.0	2.5	—	—	—	—	2.5
Subtotal		6	6	8	10	11	13	14	14	14
Flight Data		1	1	1	1	2	2	2	2	2
Total		7	7	9	11	13	15	16	16	17
Manning Factor		0.88	0.88	1.13	1.38	1.63	1.88	2.00	2.00	2.13

*0.5 Man Required to Match Companion Sector

Table 2.30b SFO Staffing Versus Traffic Growth Ratio -- Level 4

NO RNAV	1974	TRAFFIC GROWTH RATIO								
Sector	OPS	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
Woodside Final	27	1.0	1.0	1.0	2.5	—	—	—	—	2.5
Foster Final	20	1.0	1.0	1.0	1.5*	1.5*	1.5*	2.5	2.5	2.5
South Feeder	18	1.0	1.0	1.0	1.0	1.0	1.0	1.5*	1.5*	1.5*
North Feeder	26	1.0	1.0	1.0	1.0	1.0	2.0	2.5	2.5	2.5
Sutro Departure	23	1.0	1.5*	1.5*	1.5*	2.5*	2.5*	2.5	2.5	2.5
Richmond Departure	38	1.0	1.5	2.5	—	—	—	—	—	2.5
Subtotal		6	7	8	10	11	12	14	14	14
Flight Data		—	—	—	—	0	—	—	—	—
Total		6	7	8	10	11	12	14	14	14
Manning Factor		0.75	0.88	1.00	1.25	1.38	1.50	1.75	1.75	1.75

100% RNAV	1974	TRAFFIC GROWTH RATIO								
Sector	OPS	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
Woodside Final	27	1.0	1.0	1.0	1.0	2.0	2.5	—	—	2.5
Foster Final	20	1.0	1.0	1.0	1.0	1.0	1.5*	1.5*	2.5	2.5
South Feeder	18	1.0	1.0	1.0	1.0	1.0	1.0	1.5*	1.0	1.5*
North Feeder	26	1.0	1.0	1.0	1.0	1.0	1.0	1.5	2.0	2.5
Sutro Departure	23	1.0	1.0	1.0	1.5*	1.5*	1.5*	1.5*	1.5*	2.5
Richmond Departure	38	1.0	1.0	1.0	2.5	—	—	—	—	2.5
Subtotal		6	6	6	8	9	10	11	12	14
Flight Data		—	—	—	—	0	—	—	—	—
Total		6	6	6	8	9	10	11	12	14
Manning Factor		0.75	0.75	0.75	1.00	1.13	1.25	1.38	1.50	1.75

*0.5 Man Required to Match Companion Sector

Table 2.30C SFO Staffing Versus Traffic Growth Ratio -- Level 6

NO RNAV Sector	1974 OPS	TRAFFIC GROWTH RATIO 1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
Woodside Final	27	1.0	1.0	1.0	1.0	1.0	2.0	—	—	2.0
Foster Final	20	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0
South Feeder	18	1.0	—	—	—	—	—	—	—	1.0
North Feeder	26	1.0	—	—	—	—	—	—	—	1.0
Sutro Departure	23	1.0	1.0	1.0	1.0	1.0	2.0	—	—	2.0
Richmond Departure	38	1.0	1.0	2.0	—	—	—	—	—	2.0
Subtotal		6	6	7	7	7	9	9	9	10
Flight Data		—	—	—	—	0	—	—	—	—
Total		6	6	7	7	7	9	9	9	10
Manning Factor		0.75	0.75	0.88	0.88	0.88	1.13	1.13	1.13	1.25

100% RNAV Sector	1974 OPS	TRAFFIC GROWTH RATIO 1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
Woodside Final	27	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0	2.0
Foster Final	20	1.0	—	—	—	—	—	—	—	1.0
South Feeder	18	1.0	—	—	—	—	—	—	—	1.0
North Feeder	26	1.0	—	—	—	—	—	—	—	1.0
Sutro Departure	23	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0*	2.0
Richmond Departure	38	1.0	1.0	1.0	2.0	—	—	—	—	2.0
Subtotal		6	6	6	7	7	7	8	9	9
Flight Data		—	—	—	—	0	—	—	—	—
Total		6	6	6	7	7	7	8	9	9
Manning Factor		0.75	0.75	0.75	0.88	0.88	0.88	1.00	1.13	1.13

*Needed for Whole-Man Increment

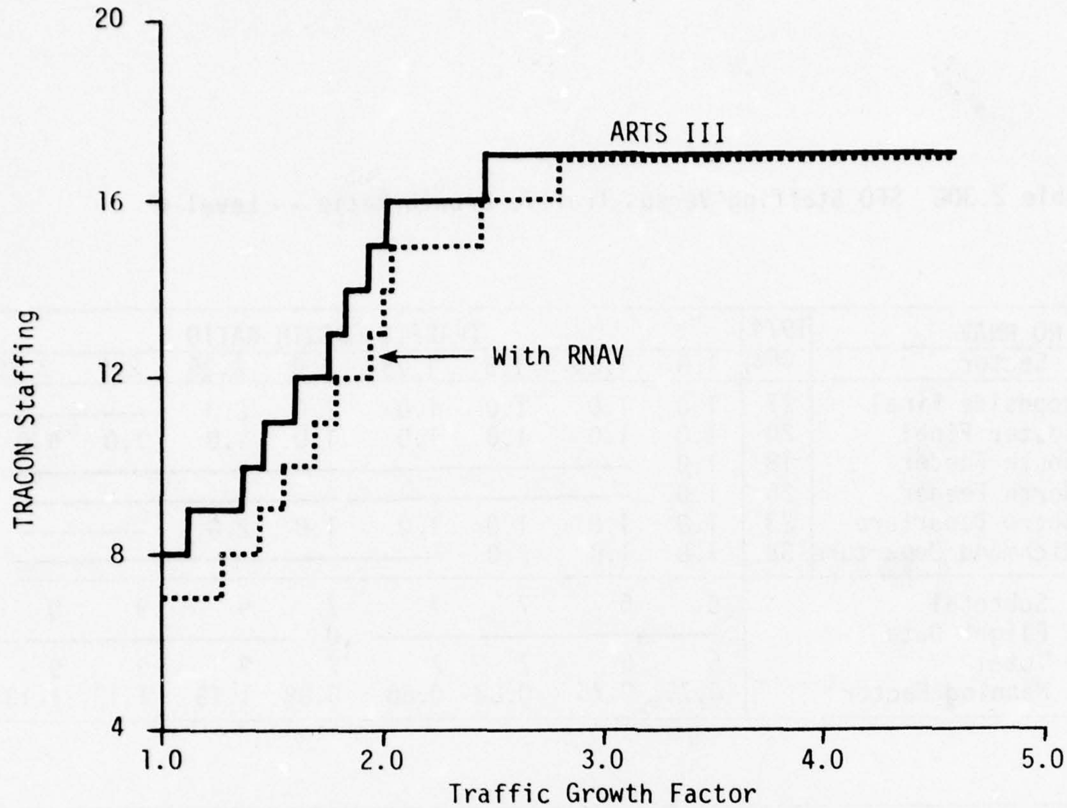

Figure 2.6a Bay TRACON Staffing Requirement - Level 1

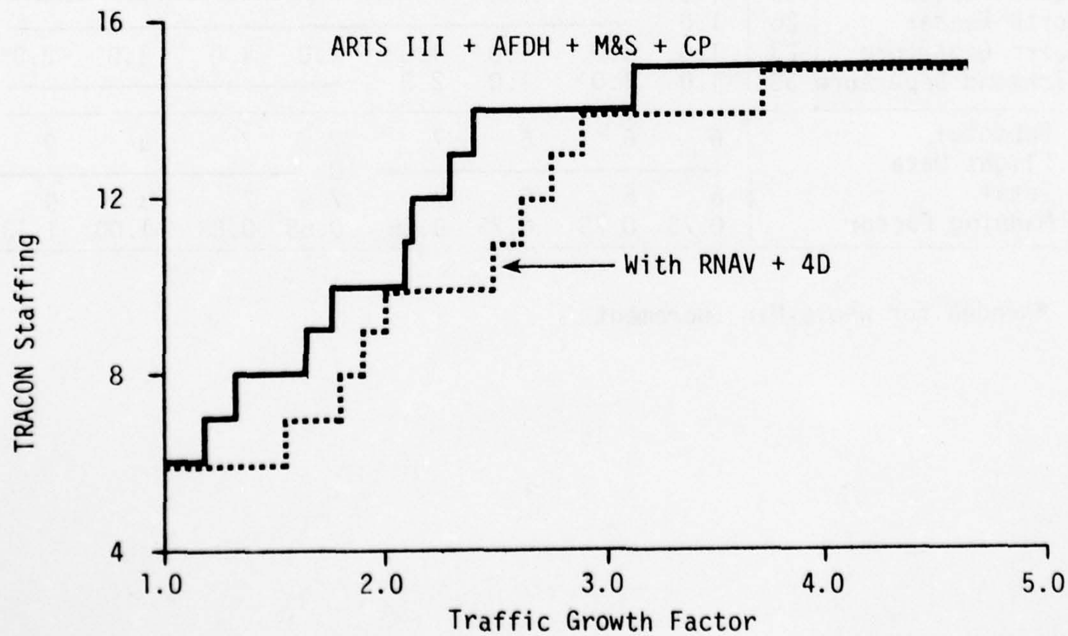

Figure 2.6b Bay TRACON Staffing Requirement - Level 4

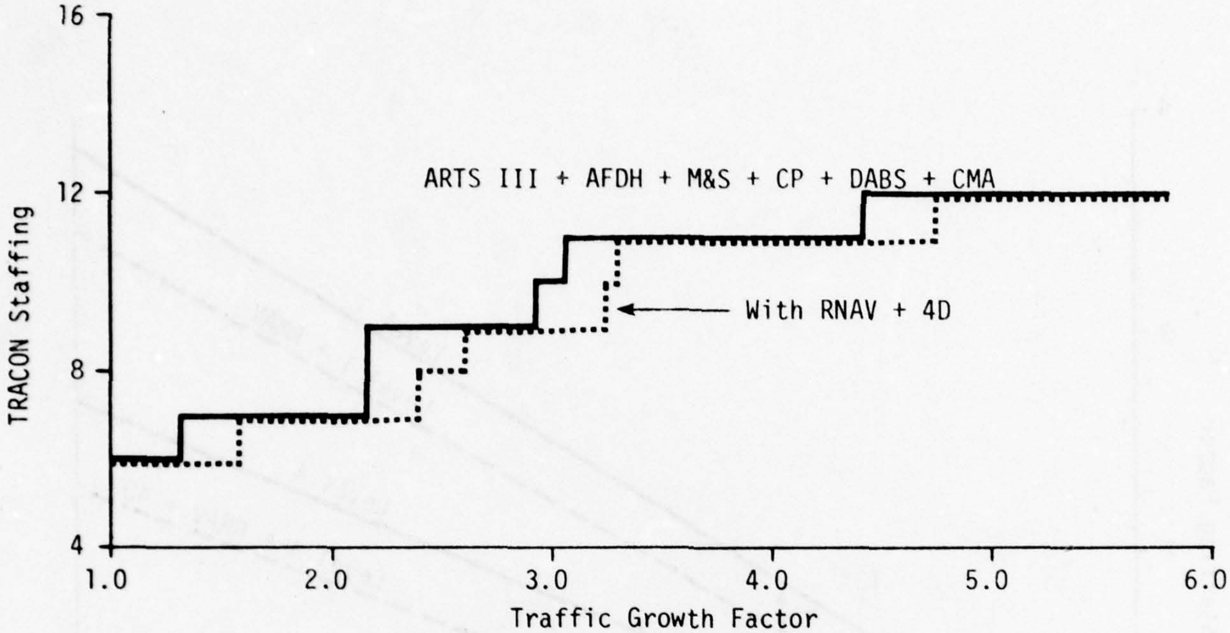

Figure 2.6c Bay TRACON Staffing Requirement - Level 6

At this point it is desirable to approximate the trends shown in Figure 2.6 with linear or quadratic relationships so that useful, easily applied functional relationships of staffing to traffic are available for extrapolation of the staffing requirements to other terminals. In the curve fitting process, the final (highest traffic) data points have been omitted since they represent the regions where the controllers are saturated. For example, in Figure 2.6a data up to a staffing level of sixteen, but not seventeen, were included. Even though the relationships appear reasonably linear, quadratic fits were tried, although the results were not good when extrapolation beyond the range of the data used was done. As is common with second order curve fits, minor changes in the data selected for inclusion wildly change the nature of the curves in the extrapolated region. With linear fits this does not occur, and so linear relationships were selected here. The results are shown in Figure 2.7. For

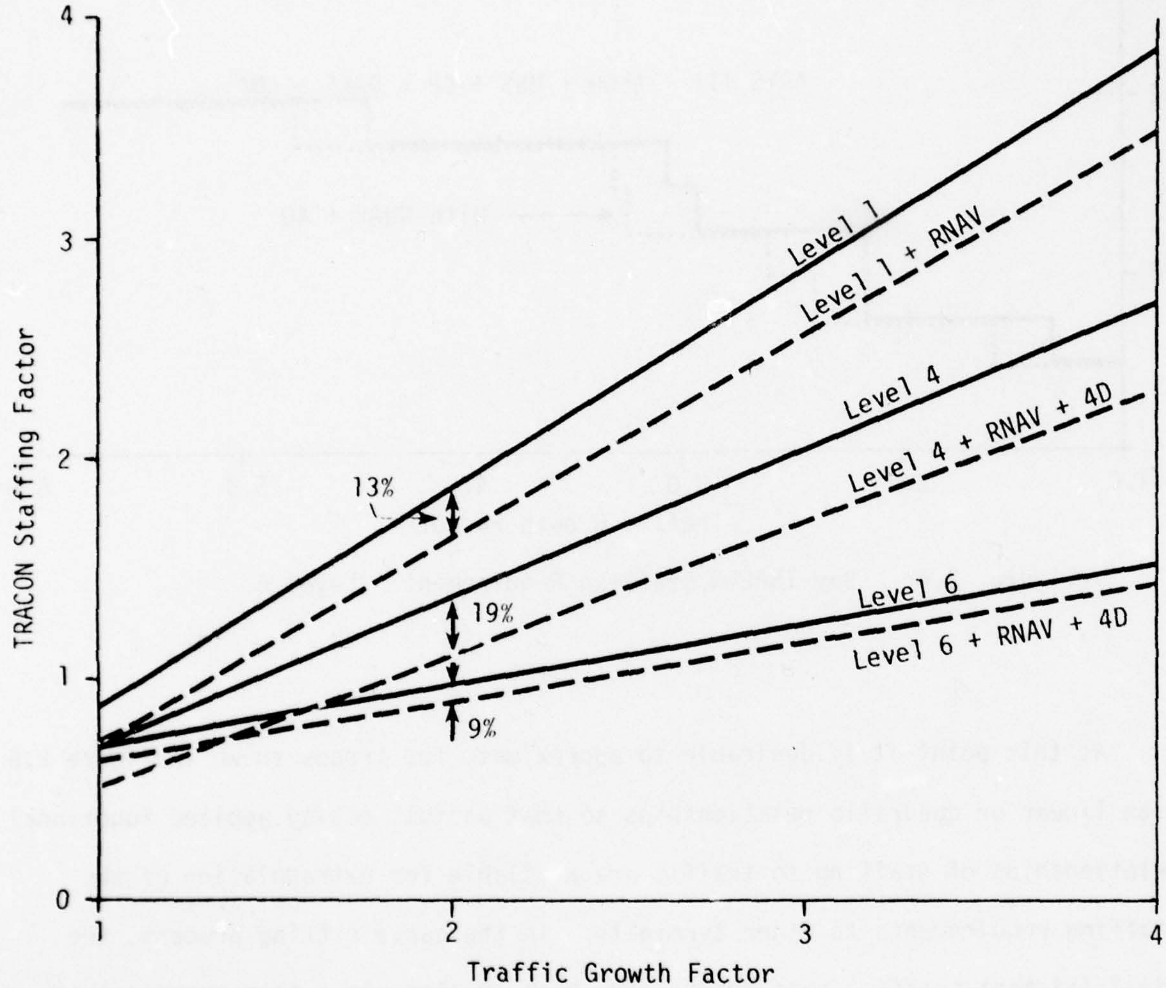

Figure 2.7 Linear Relations of Staffing to Growth Factor

purposes of example, the RNAV percent reduction at a traffic growth factor of 2.0 are shown on the graph. As would be expected from the results shown in Figure 2.5, the RNAV impact is largest at level 4, and smallest at level 6. It is significant to recognize that this result has an additional interpretation, however, when viewed from the standpoint of the additional traffic growth allowed

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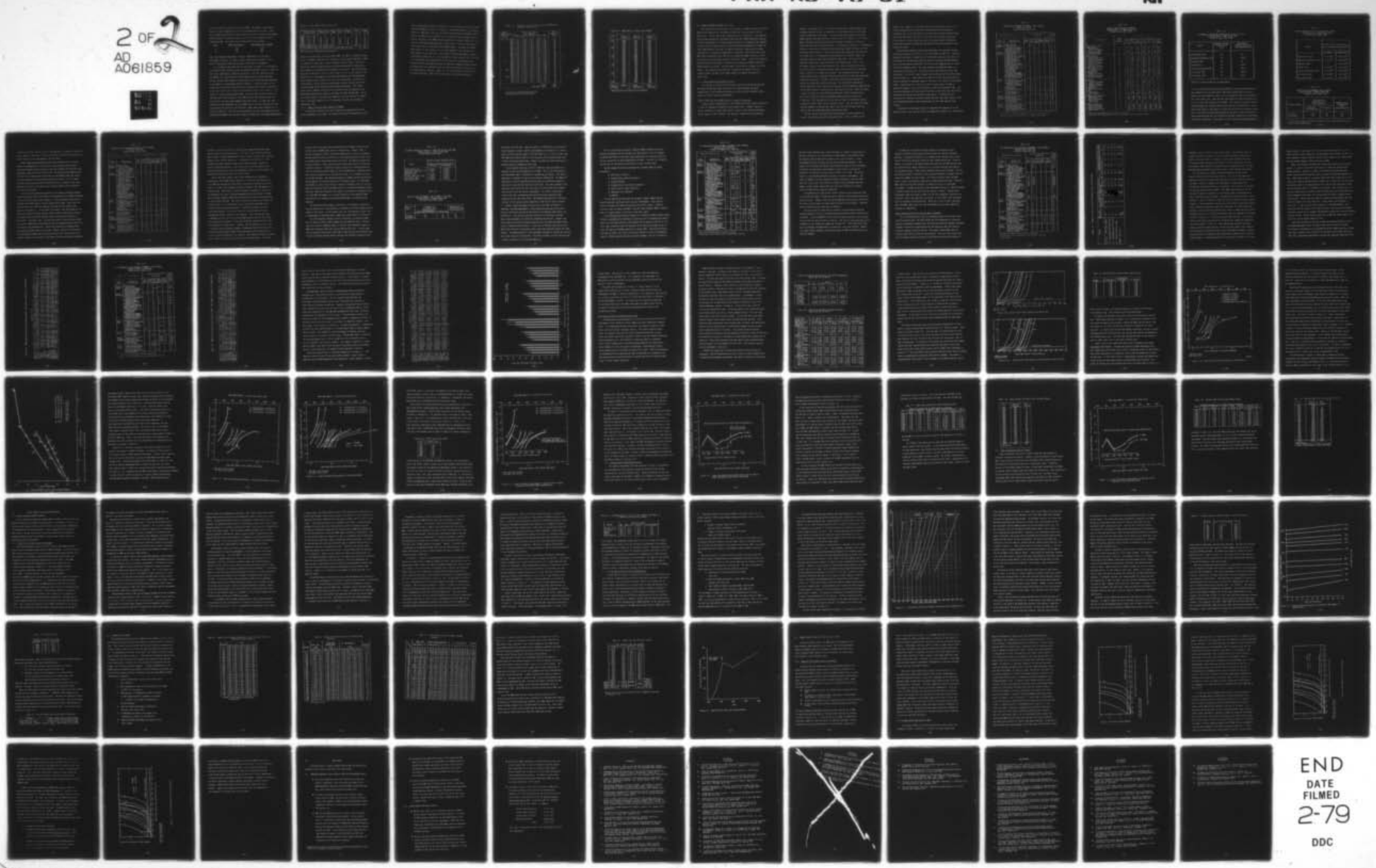

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for a given staffing factor as a result of RNAV. For example, in the level 1 case at a traffic growth factor of 2.0 the staffing factor is 1.874. In the level 1 RNAV case the traffic growth factor will reach 2.273 before an equivalent staffing factor is reached, an increase of 14% in traffic growth for the 13% staffing savings. The results for the three cases are as follows:

Level	RNAV Staff Benefit	Equivalent Traffic Growth
1	13%	14%
4	19%	21%
6	9%	16%

Thus, even though the magnitude of the basic RNAV benefit in the level 6 environment is only 9%, it allows a traffic growth factor increase of 16%, which is even greater than that available in the level 1 environment.

As an example of the application of the trends in Figure 2.7, an evaluation of the overall RNAV staffing savings for Oakland Bay TRACON is given in Table 2.31. The traffic growth data is taken from Table 2.32. The 1976 staffing for the Bay TRACON is 51 which does not include support and data systems personnel, but does include those involved in controlling traffic other than that operating at SFO (which is a considerable amount of traffic). Listed in Table 2.31 are projections (at five year intervals) of the required staff, based on the traffic growth data in the second column and the projection curve fits in Figure 2.7, for levels 1, 4 and 6, with and without RNAV. As may be seen from that figure, the straight line fit for the Level 1 case does not cross the Staffing Factor axis precisely at 1.00, but rather somewhat below that figure. In order that interpretations of the enhancement level and RNAV effects will not be biased, the staffing projected from Figure 2.7 for 1976 (45), rather than actual staffing (51), is listed in Table 2.31. From the various projections in that table phased staff projections are assembled in the last two columns corresponding to the assumed implementation

Table 2.31 Bay TRACON Staffing Projections

Year	Traffic Growth	Level 1 Staff	Level 1 + RNAV	Level 4 Staff	Level 4 +RNAV	Level 6 Staff	Level 6 + RNAV	Phased Staff	Phased + RNAV
1976	1.0	45*						45	45
1980	1.12	51	41	39	29			51	51
1985	1.21	56	45	42	32	39	35	42	32
1990	1.28	59	48	44	34	40	35	40	35
1995	1.31	61	50	45	35	40	36	40	36
2000	1.35	63	52	47	36	41	36	41	36
20 year savings over Level 1, Man-years								336	
19 year RNAV Savings over Phased Staff Without RNAV, Man-years									104

*Adjusted Using Extrapolation Relationship

scenario discussed above, with and without RNAV + 4D impact. Below the "Phased Staff" (non-RNAV) column the total man-years of staff savings from 1981 to 2000 in comparison to the "Level 1 Staff" (nominal) case are listed. These were derived by linearly interpolating to get staffing projected for each year in each column, and calculating the difference for each year. The total man-years projected in the Level 1 case over the 20 years is 1171, so the savings of 336 amounts to 28.7% attributable to the phased implementation of the enhancement levels through Level 6, which is of course very significant. Of even more significance is the fact that the enhancements actually stop and reverse the staffing growth trend inevitable without UG3RD enhancements. The further benefit due to RNAV was derived similarly through linear interpolation, but where RNAV capability was phased in uniformly from 1982 through 1985. The 19 year staff savings in man-years due to RNAV over and above the Level 6 enhancement is 104, which amounts to a 12.5% additional savings over the phased enhancement case.

2.1.3 Impact Projections Over Twenty-six TRACONS

A projection of benefits due both to the phased implementation of the UG3RD enhancements and of RNAV + 4D capability has been performed based on the

traffic projections contained in Table 2.32. Also listed in that table are the 1976 base TRACON staff sizes for reference. The method employed in projecting results is identical to that just described for the Oakland Bay TRACON. Annual results for three cases (continued level 1 capability, phased implementation to Level 6, and Level 6 plus RNAV and 4D capability) are listed in Table 2.33. The value for 1976 staffing was adjusted using the Level 1 curve fit relationship, as was done before for the Oakland Bay TRACON example. The grand total RNAV +4D savings over the 19 years it is in effect amounts to 3715 man years for these twenty-six terminal areas. At an annual 1975 wage and benefits estimate of $24,795 per controller [7], this amounts to a total savings of $92.1 million, or a 1976 present value equivalent of $23.8 million at a 10% discount rate. Standard FAA staffing formulas provide for additional support personnel roughly in proportion to the controller staff size (this is discussed in reference 8). The proportionality constant is about 22%. If this continues to hold true in the UG3RD environment, then staff savings would be increased accordingly.

Table 2.32 Terminal Traffic Forecasts [20] and TRACON Radar Controller Staffing [21]

TRACON (Major Airports Served)	Traffic Level Ratio to 1976 Base					1976 Controller Staff
	1980	1985	1990	1995	2000	
JFK + LGA + EWR	1.18	1.40	1.56	1.59	1.61	125
PHL	1.25	1.40	1.41	1.41	1.41	51
DCA	1.05	1.05	1.05	1.05	1.05	48
MCI	1.19	1.46	1.73	1.95	2.09	32
STL	1.16	1.19	1.20	1.22	1.24	39
BOS	1.19	1.41	1.49	1.49	1.49	41
ORD	1.04	1.04	1.04	1.04	1.04	87
CLE	1.24	1.39	1.43	1.43	1.43	31
DTW	1.22	1.32	1.32	1.32	1.32	58
MSP	1.25	1.56	1.90	2.22	2.55	31*
IND	1.27	1.59	1.72	1.72	1.72	40
SEA	1.18	1.43	1.82	2.19	2.54	32
DEN	1.14	1.22	1.23	1.23	1.23	32
ATL	1.22	1.38	1.38	1.38	1.38	57
CVG	1.23	1.64	2.16	2.66	3.16	20
MEM	1.24	1.63	2.13	2.37	2.46	31
MIA	1.24	1.59	1.80	1.80	1.80	45
TPA	1.29	1.70	2.17	2.62	3.08	39
DAL + DFW	1.14	1.32	1.42	1.42	1.42	71
MSY	1.22	1.52	1.83	2.13	2.40	15
LAS	1.21	1.29	1.33	1.36	1.40	27
LAX	1.23	1.23	1.23	1.23	1.23	41
OAK + SFO	1.12	1.21	1.28	1.31	1.35	51
PHX	1.34	1.62	1.73	1.73	1.73	36
PIT	1.21	1.37	1.42	1.47	1.52	31
IAH	1.21	1.48	1.77	1.90	2.03	35
					TOTAL	1146
					Adjusted** Total	1008

*1974 Value; 1976 Value not available
**Using Extrapolation Relationship

Table 2.33 RNAV Impact at Twenty-eight TRACONS

Year	Level 1 Staffing	Level 4,6 (Phased)	Level 4,6 + RNAV
1976	1008*	1008	1008
7	1063	1063	1063
8	1117	1117	1117
9	1172	1172	1172
1980	1226	1226	1226
1	1267	1194	1194
2	1308	1161	1102
3	1350	1129	1010
4	1391	1096	918
1985	1432	1064	825
6	1461	1045	813
7	1491	1026	801
8	1520	1006	789
9	1550	987	777
1990	1579	968	765
1	1595	972	769
2	1611	977	774
3	1627	981	778
4	1643	986	783
1995	1659	990	787
6	1674	994	791
7	1688	998	795
8	1703	1002	798
9	1717	1006	802
2000	1732	1010	806
Total	36584	26178	22463
Savings		10406(28%)	3715(14%)

*Adjusted Using Extrapolation Relationship

2.2 ENROUTE CONTROLLER PRODUCTIVITY STUDY

This section presents the analysis of the impact of RNAV on enroute controller workload and productivity, including an evaluation of the projected staffing implications. As was done in the terminal area case in Section 2.1, this analysis was performed presuming an environment where the other UG3RD enhancement programs are being implemented in an orderly manner according to a reasonable time schedule. In order that the schedule used may include the phased implementation of RNAV and other UG3RD features, the impact of RNAV was assessed as each successive major UG3RD feature is introduced, independent of scheduling. This would allow overall RNAV impact assessments to be made for any reasonable schedule scenario, and not be limited to that particular scenario used in this study. In the first subsection below the enroute environment is analyzed and the impacts of RNAV and the other UG3RD features are derived. Staffing impact is derived for a sample set of nine sectors. The remaining two subsections extrapolate the results first to a complete center, and then to all CONUS centers, and express the results in dollar terms.

2.2.1 Enroute Workload and Capacity Effects

This section is divided into three parts, the first of which discusses the philosophy behind RNAV impact evaluation, the second presents the actual computations of sector workload and capacity, while the third interprets these results in terms of staffing requirements.

Effects of RNAV and Other UG3RD Features on Controller Workload

Enroute control responsibilities are divided into sectors which are defined in terms of geographical boundaries and altitude limits. However, there are several categories of sectors which differ in terms of the functions performed and the types of traffic handled. The two basic categories are low and high

altitude. In greater detail, sector types include high altitude enroute, high altitude transition (arrival or departure), low altitude enroute, low altitude arrival or departure, and oceanic. The basic tasks which control sector team members perform have been analyzed in detail by SRI in references 5, 6, 22 and 23. Many of the data collection and analysis techniques utilized are similar to those used for terminal workload analysis, as described in Section 2.1. Reference 22 presents an analysis of Los Angeles Center operations, while reference 5 presents an Atlanta Center analysis. The Altanta analysis was selected as the basis for this study since it is probably more representative of a typical center, and since more types of sectors were analyzed in that study. Two basic sector staffing configurations were evaluated in the Atlanta study. First, a 2.5 man sector, consisting of radar controller (R), a data controller (D), and an assistant (A) who is shared with another sector team, and then a 3.5 man team, where a tracker (T) is added, were studied. The R-controller performs air/ground communications, some data input/output operations (flight data processing/radar data processing -- FDP/RDP), some flight strip processing operations, surveillance tasks and conflict processing. The D-controller performs most FDP/RDP operations, some flight strip processing and all interphone communications. The assistant delivers flight strips for the sectors he serves. When the tracker is added, he takes over the FDP/RDP operations and flight strip processing, while the D-controller handles interphone communications and assists the T-controller. SRI analyzed the 3.5 man team as a means of increasing capacity by adding personnel other than by splitting sectors. This was found to increase capacity somewhat in the base NAS Stage A case, but did not have significant effects after the UG3RD enhancement features were added.

The SRI analysis technique breaks workload down into the categories of routine, surveillance and conflict processing tasks. This is similar to the

terminal case. However, it was found that the sector workload capacity limit could be determined not only by the 48 man-minute per hour R-controller saturation limit, as in the terminal case, but also by an R/D-controller team limit of 66 man-minutes per hour if that limit was the greater constraint. In the analysis of seven study area sectors, most were capacity limited by R-controller workload, although the R/D-controller team limit applied in the case of one sector.

Routine event categories and minimum performance time estimates derived by SRI (particularly in references 6 and 22) are shown in Table 2.34. The event categories are similar to those used in the terminal area case (see Table 2.4) except that Data Entry/Display Operation becomes Flight Data Processing/Radar Data Processing Operation (FDP/RDP), and Face-to-Face Communications is called Direct Voice Communications. The event categories and detailed events are tailored to the enroute case. The routine event times shown are sector team man-seconds. The routine event frequencies were measured for the seven sectors listed in Table 2.35. These sectors are those at or near the Atlanta terminal area and represent a reasonable subset of the total of 41 sectors in the Atlanta Center. Routine team task time per aircraft for each sector is found by summing the products of the event frequencies times the performance times. The resulting combination of total routine task time, surveillance time and conflict processing time defines the workload at that sector. By determining the relationship of workload to aircraft handled per hour, the sector capacity limit may be determined based on the 66 man-minutes per hour team workload limit criteria.

R-Controller surveillance workload is determined the same way as in the terminal control case, and the results are summarized in Table 2.36. R-controller

Table 2.34

ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
2.5-MAN SECTOR TEAM
SYSTEM 1A--NAS STAGE A BASE

Routine Control Event Description		Minimum Task Performance Time* (man-sec/task)					Minimum Event Performance Time (man-sec/event)
Event Function	Basic Event and Supplemental Event	A/G Communication	FDP/RDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication†	
Control jurisdiction transfer	Handoff acceptance		2	1			3
	Flight data update		3				3
	Intersector coordination				7	6	13
	New flight strip preparation			10			10
	Handoff initiation-automatic			1			1
	Manual initiation-silent		3				3
	Intersector coordination				7	6	13
Traffic structuring	Initial pilot call-in	4		1			5
	Flight data altitude insert		3	1			4
	Altitude instruction	4		2			6
	Flight data altitude amendment		3				3
	Intersector coordination				5	6	11
	Heading instruction	5		2			7
	Flight data amendment		10				10
	Intersector coordination				5	6	11
	Speed instruction	5		2			7
	Intersector coordination				5	6	11
	Altimeter setting instruction	3		1			4
	Runway assignment instruction	3					3
	Pilot altitude report	5		2			7
	Flight data altitude insert		3				3
	Pilot heading report	5		2			7
	Pilot speed report	5		2			7
	Traffic advisory	4					4
	Transponder code assignment	4					4
	Flight data code amendment		3	2			5
	Miscellaneous A/G coordination	5					5
	Frequency change instruction	4		1			5
	Intersector coordination				4	6	10
Pilot request	Altitude revision	6		2			8
	Flight data altitude amendment		3				3
	Intersector coordination				5	6	11
	Route/heading revision	8		2			10
	Flight data route amendment		10				10
	Intersector coordination				6	8	14
	Speed revision	6		2			8
	Clearance delivery	20	3	2			25
	Miscellaneous pilot request	8					8
Pointout	Pointout acceptance				7	8	15
	Data block suppression		3				3
	Pointout initiation		3	2	7	8	20
General intersector coordination	Control instruction approval				5	6	11
	Planning advisory				5	6	11
	Aircraft status advisory				5	6	11
	Control jurisdiction advisory				6	6	12
	Clearance delivery			2	20	6	28
	Flight data update		3				3
General system operation	Flight data estimate update		1	3			4
	Data block/leader line offset		2				2
	Data block forcing/removal		3				3
	Miscellaneous data service		3				3
	Flight strip sequencing/removal			2			2
	Equipment adjustment		3				3

*Task performance time estimates are based on data collected at the Los Angeles Center.

†Indicated value is double the measured direct voice communication time duration.

Table 2.35

ROUTINE EVENT FREQUENCY ESTIMATES
ATLANTA CENTER, 2.5-MAN SECTOR TEAM
SYSTEM 1A--NAS STAGE A BASE

Routine Control Event	Event Minimum Performance Time† (man-sec/event)	Event Frequency per Sector (event/aircraft)						
		High Enroute (36) Allatoona	Departure Transition (37) Crossville	Departure (38) North Departure	Arrival (41) Norcross	Arrival Transition (42) Lanier	Low Arrival (46) Commerce	Low Enroute (52) Hinch Mountain
Control jurisdiction transfer								
Handoff acceptance	3	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Flight data update	3	0	0	0	0	0	0	0
Intersector coordination	13	0	0*	0.13	0.12	0	0.33	0.99
New flight strip preparation	10	0	0	0	0	0	0.17	0.09
Handoff initiation-automatic	1	0.25	0.17	0	0.29	0.40	0.25	0.18
Manual initiation-silent	3	0.75	0.83	1.00	0.71	0.60	0.75	0.82
Intersector coordination	13	0	0*	0.19	0.06	0	0.58	0.55
Traffic structuring								
Initial pilot call-in	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Flight data altitude insert	4	0	0	0	0	0	0.17	0.09
Altitude instruction	6	1.04	1.48	1.19	1.47	1.95	1.08	1.00
Flight data altitude amendment	3	0	0.09	0	0.88	0.10	0	0.18
Intersector coordination	11	0	0.25*	0.06	0.18	0.25	0.25	0.27
Heading instruction	7	0.50	0.65	1.31	0.82	0.30	0.17	0.45
Flight data route amendment	10	0.17	0.13	0	0	0	0.08	0.09
Intersector coordination	11	0	0*	0.06	0.06	0	0	0.09
Speed instruction	7	0	0	0	1.00	0.25	0	0
Intersector coordination	11	0	0.10*	0	0.12	0.10	0	0
Altimeter setting instruction	4	0	0	0.25	0.94	0	0.25	0.18
Runway assignment instruction	3	0	0	0	0	0	0	0
Pilot altitude report	7	0.13	0.30	0.25	0.82	0.40	0.42	0.45
Flight data altitude insert	3	0	0	0	0	0	0	0
Pilot heading report	7	0.08	0.26	0	0.41	0.15	0.67	0.64
Pilot speed report	7	0	0	0	0.24	0.10	0	0.09
Traffic advisory	4	0.67	0.17	0	0.06	0.30	0.17	0.09
Transponder code assignment	4	0	0	0.19	0.18	0	0.08	0.18
Flight data code	5	0	0	0	0	0	0	0.18
Miscellaneous A/G coordination	5	0	0	0	0	0	0.08	0.09
Frequency change instruction	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Intersector coordination	10	0.04	0*	0	0	0	0	0
Pilot request								
Altitude revision	8	0.08	0.17	0	0.24	0.05	0.17	0.09
Flight data altitude amendment	3	0.04	0.13	0	0.18	0.05	0	0
Intersector coordination	11	0.04	0*	0	0.06	0	0	0
Route/heading revision	10	0.04	0	0	0	0.05	0	0
Flight data route amendment	10	0.04	0	0	0	0	0	0
Intersector coordination	14	0	0.05*	0	0	0.05	0	0
Speed revision	8	0	0	0	0	0	0	0
Clearance delivery	25	0	0	0	0	0	0	0.09
Miscellaneous pilot request	8	0	0	0	0	0	0	0
Pointout								
Pointout acceptance	15	0	0.13	0.06	0	0.05	0.08	0
Data block suppression	3	0	0.13	0	0	0.05	0	0
Pointout initiation	20	0.04	0.09	0.44	0.18	0.15	0	0.18
General intersector coordination								
Control instruction approval	11	0.08	0.30*	0.56	0.35	0.30	0.58	0.36
Planning advisory	11	0.08	0.10*	0.13	0.24	0.10	0.33	0
Aircraft status advisory	11	0.08	0.10*	0.13	0.18	0.10	0.08	0.55
Control jurisdiction advisory	12	0.13	0.05*	0.19	0.29	0.05	0.17	0.18
Clearance delivery	28	0	0*	0	0	0	0.08	0.18
Flight data update	3	0	0	0	0	0	0	0.18
General system operation								
Flight data estimate update	4	0.29	0.48	1.00	0.53	0.70	0.50	1.18
Data block/leader line offset	2	0.50†	0.50†	0.50†	0.50†	0.50†	0.50†	0.50†
Data block forcing/removal	3	1.00†	1.00†	1.00†	1.00†	1.00†	1.00†	1.00†
Miscellaneous data service	3	0.25	0.04	0	0.12	0.15	0.08	0.36
Flight strip sequencing/removal	2	3.00†	3.00†	3.00†	3.00†	3.00†	3.00†	3.00†
Equipment adjustment	3	0.10†	0.10†	0.10†	0.10†	0.10†	0.10†	0.10†

*Indicated value estimated, assumed identical to Sector 42 of the Atlanta Center.

†Indicated value estimated, based on data previously collected at the Los Angeles Center and on Atlanta Center observations.

Table 2.36

R CONTROLLER SURVEILLANCE WORKLOAD WEIGHTING, BY SECTOR
ATLANTA CENTER, 2.5-MAN SECTOR TEAM
SYSTEM IA--NAS STAGE A BASE

Sector	Aircraft Average Transit Time (min)	Surveillance Workload Weighting* (man-sec/aircraft)
High enroute (36)	20	25
Departure transition (37)	21	26.25
Departure (38)	12	15
Arrival (41)	19	23.75
Arrival transition (42)	18	22.5
Low arrival (46)	21	26.25
Low enroute (52)	14	17.5

*Based on 1.25 man-seconds per aircraft-minute

conflict processing workload has been estimated for each sector based upon the route geometries and relative traffic densities involved, which are used to compute conflict frequencies (Table 2.37), and measured conflict event performance times (Table 2.38). Note that the time required to resolve crossing conflicts is twice that required for overtakes. This results since radar vector or altitude changes are involved, which require two sets of instructions: one to resolve the conflict, and another to return the aircraft to the original flight plan. Total R/D-controller team workload per aircraft is then the sum of the team routine workload plus the R-controller workload categories of surveillance and conflict processing. Since the per aircraft conflict processing workload is

Table 2.37

ESTIMATED FREQUENCY OF CONFLICT EVENTS PER SECTOR
ATLANTA CENTER, 2.5-MAN SECTOR TEAM
SYSTEM 1A--NAS STAGE A BASE

Sector	Conflict Event Frequency Factor [(conflicts/hr)/(aircraft/hr)^2]	
	Crossing	Overtaking
High enroute (36)	4.8×10^{-3}	0.9×10^{-3}
Departure transition (37)	4.4×10^{-3}	0.5×10^{-3}
Departure (38)	0	0.7×10^{-3}
Arrival (41)	2.7×10^{-3}	6.4×10^{-3}
Arrival transition (42)	3.5×10^{-3}	5.8×10^{-3}
Low arrival (46)	6.6×10^{-3}	0.7×10^{-3}
Low enroute (52)	5.3×10^{-3}	4.3×10^{-3}

Table 2.38

CONFLICT EVENT PERFORMANCE TIME ESTIMATES
ATLANTA CENTER, 2.5-MAN SECTOR TEAM
SYSTEM 1A--NAS STAGE A BASE

Conflict Event	Minimum Task Performance Time* (man-sec/task)		Minimum Event Performance Time (man-sec/event)
	Detection and Assessment	Resolution	
Crossing	20	40	60
Overtaking	20	20	40

*Based on data collected at the Los Angeles Center and observations of Atlanta Center operations.

a function of traffic density, overall team workload is a quadratic function of traffic density. Therefore, in order to determine the team capacity using the 66 man-minute criteria, the quadratic must be solved.

Sector capacity based upon the R-controller workload limit of 48 man-minutes is accomplished in a similar way, except that the routine events actually performed by the R-controller have been isolated; the resulting event performance times are listed in Table 2.39. The routine event frequency data in Table 2.35 are then multiplied by these new performance times and summed to yield R-controller routine event workload per aircraft. This is summed with the surveillance and conflict workload factors, as before, to get total workload per aircraft, from which sector capacity based on the R-controller limit may be calculated.

Each of the three workload categories was analyzed to determine whether there would be any impact in workload to be expected due to an RNAV environment. In the case of the routine task category, a survey of potential data sources from which such RNAV impacts could be determined was made. Recall that the New York real time simulation study [9] was used for the terminal area analysis of Section 2.1. It was shown, for example, that the existence of an RNAV route structure reduced routine lateral control instructions (vectors) by factors of 60% to 85% and routine altitude instructions by factors of 48% to 94% (see Table 2.18). The only data source of any similarity found was again a NAFEC real time simulation, but of enroute/transition sectors in the Chicago area (reference 24). Significant reductions to communications workload were demonstrated in this study. However, because of the design of the experiments (common route structures were not used, as they were in the terminal study) and limitations to the data collection and analysis techniques

Table 2.39

R-CONTROLLER EVENT MINIMUM PERFORMANCE TIME ESTIMATES
2.5-MAN SECTOR TEAM
SYSTEM 1A--NAS STAGE A BASE

Routine Control Event Description		Minimum Task Performance Time (man-sec/task)					Minimum Event Performance Time (man-sec/event)
Event Function	Basic Event and Supplemental Event	A/G Communication	FDP/EDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication	
Control jurisdiction transfer	Handoff acceptance						
	Flight data update						
	Intersector coordination					3	3
	New flight strip preparation						
	Handoff initiation-automatic						
	Manual initiation-silent						
	Intersector coordination					3	3
Traffic structuring	Initial pilot call-in	4		1			5
	Flight data altitude insert			1			1
	Altitude instruction	4		2			6
	Flight data altitude amendment						
	Intersector coordination					3	3
	Heading instruction	5		2			7
	Flight data amendment						
	Intersector coordination					3	3
	Speed instruction	5		2			7
	Intersector coordination					3	3
	Altimeter setting instruction	3		1			4
	Runway assignment instruction	3					3
	Pilot altitude report	5		2			7
	Flight data altitude insert						
	Pilot heading report	5		2			7
	Pilot speed report	5		2			7
	Traffic advisory	4					4
	Transponder code assignment	4					4
	Flight data code amendment			2			2
	Miscellaneous A/G coordination	5					5
	Frequency change instruction	4		1			5
	Intersector coordination					3	3
Pilot request	Altitude revision	6		2			8
	Flight data altitude amendment						
	Intersector coordination					3	3
	Route/heading revision	8		2			10
	Flight data route amendment						
	Intersector coordination					4	4
	Speed revision	6		2			8
	Clearance delivery	20		2			22
	Miscellaneous pilot request	8					8
Pointout	Pointout acceptance					4	4
	Data block suppression		3				3
	Pointout initiation					4	4
General intersector coordination	Control instruction approval					3	3
	Planning advisory					3	3
	Aircraft status advisory					3	3
	Control jurisdiction advisory					3	3
	Clearance delivery					3	3
	Flight data update						
General system operation	Flight data estimate update						
	Data block/leader line offset		2				2
	Data block forcing/removal		3				3
	Miscellaneous data service						
	Flight strip sequencing/removal						
	Equipment adjustment		3				3

available, it was not possible to separate those communications which were made for conflict resolution purposes. Of course, this distinction must be made in order to compute RNAV workload/capacity impact using the SRI techniques. However, since conflict impact data is available from references 25 (high altitude fast-time simulation study) and 12 (which contains a summary of conflict resolution options), it was decided to utilize that data for the conflict processing part of the SRI methodology, and to resort to analysis for determining any possible effects on routine tasks.

Each of the major routine control event categories was examined to determine any likely RNAV impact categories. It was felt that there would be no RNAV routing impacts on the Control Jurisdiction Transfer process (see Table 2.34) since sector boundaries would be crossed in the same manner as is presently done. With respect to the Pilot Request category, no revision to the probability of route or altitude amendments would be expected. Neither would Pointouts, General Intersector Coordination or General System Operation be significantly affected. The Traffic Structuring category may, however, be affected since it is in routing and traffic structuring that RNAV differs primarily from conventional navigation. Within that category the basic events were analyzed. The Initial Pilot Call-in event would be no more affected than General Intersector Coordination. Since altitude and speed assignments are not a part of an enroute RNAV route definition, those event types would not be affected. By the same reasoning, neither would the Pilot Altitude Report or Speed Report. Likewise, the informational services such as Altimeter Setting, Runway Assignment, Transponder Code, Miscellaneous A/G Coordination and Frequency Change Instructions would not be affected since enroute routing information is not involved. The remaining categories include Traffic Advisory, Heading Instruction and Pilot Heading Report. Since the

rate of traffic advisories would be expected to be somewhat affected by the conflict rate, an RNAV impact would be expected here. However, there is no way to establish a direct correlation between traffic advisory frequencies and the conflict results in reference 25 since many advisories are the result of planned traffic structuring control activities, not chance occurrences of airspace conflicts. Also, some advisories involve VFR aircraft (in the low/transition sectors). Furthermore, keying a reduction in routine workload to conflict rates would further complicate the SRI methodology. Therefore, while there would be expected to be some positive effect, it is assumed to be zero for present purposes. The remaining categories, Heading Instruction and Pilot Heading Report, are directly related to off-airways flying. In a 100% RNAV environment, no radar vector flying is necessary (enroute) since all aircraft would be navigating either along RNAV routes or user-defined preplanned routes. Therefore, these two categories are assumed to be reduced in frequency to zero in a 100% RNAV environment, or in linear proportion to the degree of RNAV participation, for purposes of determining RNAV impact on routine enroute workload.

The second workload category, surveillance, is affected in the enroute case the same way as in the terminal: by the length of time the average aircraft spends in each sector. In the enroute case this time reduction is only 1.61%. as determined in a detailed study of RNAV route length impact in reference 2.

The third workload category, conflict processing, is affected by RNAV both in terms of conflict event frequencies and resolution times. The data source for conflict frequency impact is the fast time simulation study of an RNAV route structure versus the existing VOR structure [25]. In that study conflict types are classified in more detail than the two classifications used in the SRI workload analysis method (Crossing and Overtaking categories only;

Table 2.40

ESTIMATED FREQUENCY OF CONFLICT EVENTS PER SECTOR--100% RNAV
ATLANTA CENTER, 2.5-MAN SECTOR TEAM
SYSTEM 1A-NAS STAGE A BASE

Sector	Conflict Event Frequency Factor [(Conflicts/hr)/(Aircraft/hr)^2]	
	Crossing	Overtaking
High Enroute (36)	3.8×10^{-3}	0.6×10^{-3}
Departure Transition (37)	3.5×10^{-3}	0.3×10^{-3}
Departure (38)	0	0.4×10^{-3}
Arrival (41)	2.1×10^{-3}	4.0×10^{-3}
Arrival Transition (42)	2.8×10^{-3}	3.7×10^{-3}
Low Arrival (46)	5.2×10^{-3}	0.4×10^{-3}
Low Enroute (52)	4.2×10^{-3}	2.7×10^{-3}

Table 2.41

CONFLICT EVENT PERFORMANCE TIME ESTIMATES--100% RNAV
ATLANTA CENTER, 2.5-MAN SECTOR TEAM
SYSTEM 1A--NAS STAGE A BASE

Conflict Event	Minimum Task Performance Time (man-sec/task)		Minimum Event Performance Time (man-sec/event)
	Detection & Assessment	Resolution	
Crossing	20	34	54
Overtaking	20	20	40

see Tables 2.37 and 2.38). When the results in reference 25 are regrouped in these categories, overall conflicts (nationwide) are reduced 20.9% (crossing type) and 36.8% (Overtake type) in the 100% RNAV case. In cases of lower than 100% RNAV participation conflicts were reduced by an even greater amount than a linear relationship would show. However, for simplicity the relationship is assumed linear for purposes of this study.

In the terminal area case, conflict resolution times were shown to be improved in some cases through the use of RNAV. This is also true enroute, and experimental data is available for quantifying the effects. This data is summarized in reference 12 and also discussed in reference 25. The degree of reduction in conflict resolution time was found to be different depending upon conflict type and the resolution option used. The times recorded in the experiments were controller talk times and so do not include pilot response and controller decision process requirements. As a result, considerably shorter times were recorded than the 40 and 20 second resolution times determined by SRI (see Table 2.38). The overtake type conflict is typically resolved in the same way enroute regardless of the type of route structure, i.e. through a speed adjustment (usually only in the lower altitudes) or, sometimes, altitude reassignments. RNAV capability would make the parallel offset an attractive solution to the conflict also (whereas radar vectors are problematic). This would be even more attractive in the higher altitudes, where speed adjustments are often not acceptable operationally. However, the offset shows no particular workload reduction over the speed adjustment option, and so no workload effect results. In the case of crossing type conflicts the RNAV offset and direct instructions offer significant workload savings over radar vectors. The amount measured in the experiments averaged six seconds per conflict, and so that value will be used here. Revisions to Tables 2.37 and 2.38 are given in Tables 2.40 and 2.41 for the 100% RNAV case.

Prior to calculating the specific impact of RNAV on enroute controller workload and productivity for the base case (NAS Stage A), it is of interest to examine the effects of the other UG3RD enhancements on controller workload, and the interactions of those enhancements with RNAV. This will be followed by calculations for workload and productivity for each of these cases.

The SRI studies [22,5] have considered the following levels of system performance:

- NAS Stage A (System 1)
- Automated Data Handling (System 2)
- Enroute Metering
- Automated Local Flow Control (System 3)
- Sector Conflict Probe (System 4)
- DABS Data Link (System 6)
- DABS/IPC

The two items above which were not assigned "system" numbers were not found to provide significant sector capacity improvements. Also, Conflict Alert and Flight Plan Probe were analyzed with similar results. System 5, missing in the list above, was RNAV in the SRI study; however, RNAV is studied here as it would interact with each of the other levels.

With Automated Data Handling (System 2) an Electronic Tabular Display System (ETAB) is provided which eliminates flight strips, and so eliminates the requirement for an assistant position, which reduces sector team size from 2.5 to 2.0. Also, radar controller tasks are modified, since there are no paper strips to mark, but there are FDP/RDP operations to replace them. The exact differences are shown in Table 2.42, which lists the old (System 1) values in parentheses. Overall, FDP/RDP operation workload increases somewhat, but this is offset by

Table 2.42

R-D TEAM ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
TWO-MAN SECTOR OPERATION
SYSTEM 2--AUTOMATED DATA HANDLING

Routine Control Event Description		Minimum Task Performance Time* (man-sec/task)					Minimum Event Performance Time* (man-sec/event)
Event Function	Basic Event and Supplemental Event	A/G Communication	FDP/RDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication†	
Control jurisdiction transfer	Handoff acceptance		2	0(1)			2(3)
	Flight data update		3				3
	Intersector coordination				7	6	13
	New flight strip preparation		10(0)	0(10)			10
	Handoff initiation-automatic			0(1)			0(1)
	Manual initiation-silent		1(3)				1(3)
	Intersector coordination				7	6	13
Traffic structuring	Initial pilot call-in	4	1(0)	0(1)			5
	Flight data altitude insert		3	0(1)			3(4)
	Altitude instruction	4	3(0)	0(2)			7(6)
	Flight data altitude amendment		0(3)				0(3)
	Intersector coordination				5	6	11
	Heading instruction	5	3(0)	0(2)			8(7)
	Flight data amendment		10				10
	Intersector coordination				5	6	11
	Speed instruction	5	3(0)	0(2)			8(7)
	Intersector coordination				5	6	11
	Altimeter setting instruction	3	1(0)	0(1)			4
	Runway assignment instruction	3					3
	Pilot altitude report	5	3(0)	0(2)			8(7)
	Flight data altitude insert		0(3)				0(3)
	Pilot heading report	5	3(0)	0(2)			8(7)
	Pilot speed report	5	3(0)	0(2)			8(7)
	Traffic advisory	4					4
	Transponder code assignment	4					4
	Flight data code amendment		3	0(2)			3(5)
	Miscellaneous A/G coordination	5					5
	Frequency change instruction	4	1(0)	0(1)			5
	Intersector coordination				4	6	10
Pilot request	Altitude revision	6	3(0)	0(2)			9(8)
	Flight data altitude amendment		0(3)				0(3)
	Intersector coordination				5	6	11
	Route/heading revision	8	3(0)	0(2)			11(10)
	Flight data route amendment		10				10
	Intersector coordination				6	8	14
	Speed revision	6	3(0)	0(2)			9(8)
	Clearance delivery	20	3	0(2)			23(25)
	Miscellaneous pilot request	8					8
Pointout	Pointout acceptance		3(0)		0(7)	0(8)	3(15)
	Data block suppression		3				3
	Pointout initiation		3	0(2)	0(7)	0(8)	3(20)
General intersector coordination	Control instruction approval				5	6	11
	Planning advisory				5	6	11
	Aircraft status advisory				5	6	11
	Control jurisdiction advisory				6	6	12
	Clearance delivery			0(2)	20	6	26(28)
	Flight data update		3				3
General system operation	Flight data estimate update		1	0(3)			1(4)
	Data block/leader line offset		2				2
	Data block forcing/removal		3				3
	Miscellaneous data service		3				3
	Flight strip sequencing/removal			0(2)			0(2)
	Equipment adjustment		3				3

*Revised System 1A performance times are indicated in parentheses.

†Indicated value is double the measured direct voice communication time duration.

the much larger reduction due to the elimination of flight strip processing. A few other savings are also realized due to improvements to the RDP/PVD (Plan View Display) system functioning assumed to be a part of System 2. These improvements serve to eliminate most pointout coordination workload. Also, System 2 will eliminate the General System Operation tasks of Data Block/Leader Line Offset and Data Block Forcing/Removal, which results in setting the frequencies of occurrence of those items in Table 2.35 to zero. The overall result is a significant workload savings due to System 2 improvements. The impact of RNAV will be only negligibly affected by System 2, since the RNAV sensitive factors have little effect on flight strip and FDP/RDP processing. However, percent impact should grow since the overall workload is reduced, making the RNAV savings larger by comparison.

The Automated Local Flow Control feature (System 3) was analyzed and found to be a promising means of improving overall capacity by balancing workload among adjacent sectors. However, since the SRI methodology treats sectors individually, the impact of this feature on sector workload could not be estimated. Therefore, System 2 workload results were used for System 3.

The Sector Conflict Probe feature (System 4) allows workload reductions through automation of most of the workload associated with conflict detection and assessment. It was assumed [22,5] that the probe reduces detection and assessment time per conflict event from 20 to 5 man-sec. The conflict event performance time estimates for all systems are summarized in Table 2.44. Since resolution times were not affected, the RNAV impact on resolution time is not affected. However, since RNAV affects frequency, the absolute impact of RNAV on workload will be to decrease somewhat.

The DABS Data Link/Control Message Automation enhancement feature (System 6) radically changes both routine workload and conflict resolution workload. The greatest reduction is to communications workload since so many routine instructions would be replaced by data linked instructions. There is, however, an increase to FDP/RDP workload associated with the CMA function since the controller must remain cognizant of all activities and decisions made by the automated systems. Other routine workload areas are not affected. Conflict processing workload is affected in that resolution workload is reduced since all resolution commands are data linked. This would certainly affect the RNAV impact, since it was based on reductions to communications workload. Therefore, RNAV impact on resolution workload is assumed to be zero in a 100% DABS environment. The DABS study done by SRI approached staffing in a DABS environment as normally requiring two controllers per sector, as before. Routine event performance times are listed in Table 2.43 for this assumption, referred to as System 6A. Due to the reductions in workload, a 1-man sector staff assumption was also analyzed (called System 6B). While this is not of direct importance here, the RNAV impact given the 1-man environment has also been computed for purposes of completeness.

Enroute Workload and Sector Capacity Impact Assessment

This section presents the controller workload results for the seven study sectors discussed above, and then presents the SRI methodology for assessing capacity improvements through sector splitting (and therefore manpower increases). A method is derived for approximating the SRI technique, which was based on extensive computer simulation studies. New results showing RNAV impact on staffing requirements are derived and presented. The seven study sectors used for the workload analysis discussed in the previous section were selected to

Table 2.43

R-D TEAM ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
TWO-MAN SECTOR OPERATION
SYSTEM 6A--DABS DATA LINK

Routine Control Event Description		Minimum Task Performance Time* (man-sec/task)					Minimum Event Performance Time* (man-sec/event)
Event Function	Basic Event and Supplemental Event	A/G Communication	FDP/RDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication†	
Control jurisdiction transfer	Handoff acceptance		0(2)				0(2)
	Flight data update		3				3
	Intersector coordination		2(0)		7	6	15(13)
	New flight strip preparation		10				10
	Handoff initiation-automatic						0
	Manual initiation-silent		1				1
	Intersector coordination				7	6	13
Traffic structuring	Initial pilot call-in	4	1				5
	Flight data altitude insert		3				3
	Altitude instruction	0(4)	3‡				3(7)
	Flight data altitude amendment						0
	Intersector coordination	4(0)	3(0)		5	6	18(11)
	Heading instruction	0(5)	3‡				3(8)
	Flight data amendment		0(10)				0(10)
	Intersector coordination	5(0)	10(0)		5	6	26(11)
	Speed instruction	0(5)	3‡				3(8)
	Intersector coordination	5(0)	3(0)		5	6	19(11)
	Altimeter setting instruction	0(3)	0(1)				0(4)
	Runway assignment instruction	0(3)					0(3)
	Pilot altitude report	5	3				8
	Flight data altitude insert						0
	Pilot heading report	5	3				8
	Pilot speed report	5	3				8
	Traffic advisory	4					4
	Transponder code assignment	4					4
	Flight data code amendment		3				3
	Miscellaneous A/G coordination	5					5
	Frequency change instruction	0(4)	2‡(1)				2(5)
	Intersector coordination	4(0)			4	6	14(10)
Pilot request	Altitude revision	6	3				9
	Flight data altitude amendment						0
	Intersector coordination				5	6	11
	Route/heading revision	8	3				11
	Flight data route amendment		10				10
	Intersector coordination				6	8	14
	Speed revision	6	3				9
	Clearance delivery	20	3				23
	Miscellaneous pilot request	8					8
Pointout	Pointout acceptance		3				3
	Data block suppression		3				3
	Pointout initiation		3				3
General intersector coordination	Control instruction approval				5	6	11
	Planning advisory				5	6	11
	Aircraft status advisory				5	6	11
	Control jurisdiction advisory				6	6	12
	Clearance delivery				20	6	26
	Flight data update		3				3
General system operation	Flight data estimate update		1				1
	Data block/leader line offset		2				2
	Data block forcing/removal		3				3
	Miscellaneous data service		3				3
	Flight strip sequencing/removal						0
	Equipment adjustment		3				3

*Revised System 2 performance times are indicated in parentheses.

†Indicated value is double the measured direct voice communication time duration.

‡Message cognizance.

Table 2.44 Summary of Conflict Event Performance Times, Altanta Center

System	Data Link Equipped A/C	Crossing Conflict Task Time					Overtake Conflict Task Times		
		Detection & Assessment	Resolution		Total		Detection & Assessment	Resolution	Total
			No RNAV	RNAV	No RNAV	RNAV			
1A & 1B. NAS Stage A Base	0%	20	40	34	60	54	20	20	40
2. +Automated Data Handling	0%	20	[illegible]	34	60	54	20	20	40
3. +Automated Local Flow Cont	0%	20	[illegible]	34	60	54	20	20	40
4. +Sector Conflict Probe	0%	5	[illegible]	34	45	39	5	20	25
6A&6B. +Data Link	0%	5	40	34	45	39	5	20	25
	50%	5	30	27	35	32	5	15	20
	100%	5	20	20	25	25	5	10	15

represent a cross section of control sector types. The technique used for studying the capacity effects of sector splitting requires a study area of several contiguous sectors. Therefore, a study area comprising nine high altitude and transition sectors was defined. Five of the sectors are from the original seven studied; the remaining four are adjacent sectors for which workload data was derived from similar sectors in the original study group.

The following set of tables show the workload results and sector capacity limits for the seven study sectors. Since six of the seven were capacity-limited due to R-controller workload, only the R-controller analyses are shown. Sector 52, however, was team-capacity limited, and so both R-controller and R/D team results are presented. Also, sector 52 is the only low altitude enroute sector studied. Since RNAV participation in the low altitude airspace will probably be significantly lower in percentage terms than in the high altitude airspace, a 50% RNAV participation analysis is also presented. Table 2.45 contains a detailed listing of workload in each routine category, in the surveillance category and in the conflict processing category. Values stated are workload per operation; therefore, the conflict workload presumes a nominal capacity operations rate, which is stated above the conflict processing rate value. The routine workload values are computed from the data in Tables 2.34 and 2.35. Surveillance values come from Table 2.36, and the conflict rate factors are derived by multiplying and summing the appropriate terms from Tables 2.37 and 2.38. Total workload per operation at nominal capacity, and the actual capacity, are the last items stated. Also stated in this table are the equivalent values given a 100% RNAV environment. Routine workload factors are reduced by the elimination of heading vectors and pilot heading reports. Surveillance workload is reduced by the nominal 1.61% route

length reduction. New values for conflict processing workload result from reduced conflict event frequencies and performance times (Tables 2.40 and 2.42). Total workload at nominal capacity, and the actual capacity, are stated along with the percent change in these values due to RNAV.

Table 2.45 represents the NAS Stage A base case as sectors are typically manned; i.e. with a 2.5 man team consisting of a radar man, data man and a shared assistant. Sector 52 is shown to be limited by R/D-team workload rather than R-controller workload alone by a margin of about two operations per hour. RNAV capacity benefit in percent ranges from 10.8% (sector 42) to 21.1% (sector 38), with an average figure of about 13.9%. Table 2.46 lists the event performance times for the radar/tracker (R/T) team for the alternative sector manning strategy, which is referred to as System 1B. This strategy uses a 3.5 man team consisting of the radar, tracker and data men plus a shared assistant. Event frequencies from Table 2.35 are used with this data to compute routine workload data. Surveillance and conflict processing workload remain the same as in the System 1A (2.5-man team) case. These results are presented in Table 2.47. In each case the sector capacity is increased between 2 and 5 operations per hour because of the added staffing. Note that with the added controller, Sector 52 is no longer team workload limited, but is now R-controller workload limited. Sector capacity impact due to RNAV now ranges between 12.0% and 23.7%, with an average impact of 15.8%.

Equivalent workload and capacity studies have been performed for each of the UG3RD enhancement levels considered, where the existence of an RNAV environment is considered to be a parameter with each UG3RD system level rather than being a separate level (System 5) as was done in the original SRI study. RNAV impact determination was based on the data and reasoning summarized in the

Table 2.45 RNAV Sector Workload and Capacity Impact, NAS Stage A (System 1A--2.5-Man Team)

Seconds Per Aircraft

Sector Type	High Enrt.		Dep. Trans.		Departure		Arrival		Arr.Trans.		Low Arr.		Low Enroute			Low Enroute		
Sector ID	36		37		38		41		42		46		52			52		
Workload Limit	R-Controller		R-Controller		R-Controller		R-Controller		R-Controller		R-Controller		R-Controller			R/D Team		
RNAV Partic.	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	50%	100%	0%	50%	100%
Routine:																		
A/G Comm.	19.19	16.29	21.67	17.12	22.07	15.52	35.55	29.40	23.70	21.45	21.79	17.59	24.56	21.84	19.11	24.56	21.84	19.11
FDP/RDP	4.30	4.30	4.69	4.69	4.30	4.30	4.30	4.30	4.45	4.45	4.30	4.30	4.30	4.30	4.30	14.62	14.17	13.72
Flight Strip	5.74	4.58	7.72	5.90	7.75	5.13	12.94	10.48	8.50	7.60	7.44	5.76	8.25	7.16	6.07	20.59	19.50	18.41
Interphone	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	23.07	22.85	22.62
Voice	1.51	1.51	3.78	3.78	6.35	6.17	5.70	5.52	3.70	3.70	7.52	7.52	10.23	10.09	9.96	20.46	20.18	19.92
TOTAL	30.74	26.68	37.86	31.49	40.47	31.12	58.49	49.70	40.35	37.20	41.05	35.17	47.34	43.39	39.44	103.30	98.54	93.78
Surveillance	25.00	24.60	26.25	25.83	15.00	14.76	23.75	23.37	22.50	22.14	26.25	25.83	17.50	17.36	17.22	17.50	17.36	17.22
Nom. Capacity	42	42	38	38	50	50	30	30	36	36	35	35	35	35	35	35	35	35
Conflict Rate	0.324	0.228	0.284	0.201	0.028	0.018	0.418	0.277	0.442	0.296	0.424	0.300	0.490	0.413	0.335	0.490	0.413	0.335
Conflict Wkld.	13.61	9.58	10.79	7.64	1.40	0.90	12.54	8.31	15.91	10.66	14.84	10.50	17.15	14.46	11.73	17.15	14.46	11.73
Total Per A/C	69.35	60.86	74.90	64.96	56.87	46.78	94.78	81.38	78.76	70.00	82.14	71.50	81.99	75.21	68.39	137.95	130.36	122.73
RNAV Reduction		12.2%		13.3%		17.7%		14.1%		11.1%		13.0%		8.3%	16.6%		5.5%	11.0%
Capacity	41.61	46.53	38.39	43.58	50.63	61.30	30.34	34.82	36.47	40.40	35.05	39.53	35.10	37.73	40.93	33.13	35.04	37.27
RNAV Increase		11.8%		13.5%		21.1%		14.8%		10.8%		12.8%		7.5%	16.6%		5.8%	12.5%

Table 2.46

R-T TEAM ROUTINE EVENT MINIMUM PERFORMANCE TIME ESTIMATES
ATLANTA CENTER, 3.5-MAN TEAM
SYSTEM 1B--NAS STAGE A BASE

Routine Control Event Description		Minimum Task Performance Time* (man-sec/task)					Minimum Event Performance Time* (man-sec/event)
Event Function	Basic Event and Supplemental Event	A/C Communication	FDP/RDP Operation	Flight Strip Processing	Interphone Communication	Direct Voice Communication†	
Control jurisdiction transfer	Handoff acceptance		2	1			3
	Flight data update		3				3
	Intersector coordination				0(7)		6(13)
	New flight strip preparation			0(10)			0(10)
	Handoff initiation-automatic			1			1
	Manual initiation-silent		3				3
	Intersector coordination				7	6	13
Traffic structuring	Initial pilot call-in	4		1			5
	Flight data altitude insert		3	1			4
	Altitude instruction	4		2			6
	Flight data altitude amendment		3				3
	Intersector coordination				0(5)	6	6(11)
	Heading instruction	5		2			7
	Flight data amendment		10				10
	Intersector coordination				0(5)	6	6(11)
	Speed instruction	5		2			7
	Intersector coordination				0(5)	6	6(11)
	Altimeter setting instruction	3		1			4
	Runway assignment instruction	3					3
	Pilot altitude report	5		2			7
	Flight data altitude insert		3				3
	Pilot heading report	5		2			7
	Pilot speed report	5		2			7
	Traffic advisory	4					4
	Transponder code assignment	4					4
	Flight data code amendment		3	2			5
	Miscellaneous A/C coordination	5					5
	Frequency change instruction	4		1			5
	Intersector coordination				0(4)	6	6(10)
Pilot request	Altitude revision	6		2			8
	Flight data altitude amendment		3				3
	Intersector coordination				0(5)	6	6(11)
	Route/heading revision	8		2			10
	Flight data route amendment		10				10
	Intersector coordination				0(6)	8	8(14)
	Speed revision	6		2			8
	Clearance delivery	20	3	2			25
	Miscellaneous pilot request	8					8
Pointout	Pointout acceptance				0(7)	8	8(15)
	Data block suppression		3				3
	Pointout initiation		3	2	7	8	20
General intersector coordination	Control instruction approval				0(5)	6	6(11)
	Planning advisory				0(5)	6	6(11)
	Aircraft status advisory				0(5)	6	6(11)
	Control jurisdiction advisory				0(6)	6	6(12)
	Clearance delivery			0(2)	0(20)	6	6(28)
	Flight data update		0(3)				0(3)
General system operation	Flight data estimate update		0(1)	0(3)			0(4)
	Data block/leader line offset		2				2
	Data block forcing/removal		3				3
	Miscellaneous data service		3				3
	Flight strip sequencing/removal			0(2)			0(2)
	Equipment adjustment		3				3

*Revised System 1A performance times are indicated in parentheses.

†Indicated value is double the measured direct voice communication time duration.

Table 2.47 RNAV Sector Workload and Capacity Impact, NAS Stage A (System 1B--3.5-Man Team)

Seconds Per Aircraft

Sector Type	High Enrt.		Dep. Trans.		Departure		Arrival		Arr. Trans.		Low Arr.		Low Enroute			Low Enroute		
Sector ID	36		37		38		41		42		46		52			5[illegible]		
Workload Limit	R-Controller		R-Controller		R-Controller		R-Controller		R-Controller		R-Controller		R-Controller			R/T Team		
RNAV Partic.	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	50%	100%	0%	50%	100%
Total Routine	25.66	21.60	31.51	25.14	35.09	25.74	52.55	43.76	33.30	30.15	35.89	30.01	41.98	38.03	34.08	72.82	68.28	63.75
Surveillance	25.00	24.60	26.25	25.83	15.00	14.76	23.75	23.37	22.50	22.14	26.25	25.83	17.50	17.36	17.22	17.50	17.36	17.22
Nom. Capacity	44	44	42	42	55	55	32	32	40	40	37	37	37	37	37	42	42	42
Conflict Rate	0.324	0.228	0.284	0.201	0.028	0.018	0.418	0.277	0.442	0.296	0.424	0.300	0.490	0.413	0.335	0.490	0.413	0.335
Conflict Wkld.	14.26	10.03	11.93	8.44	1.54	0.99	13.38	8.86	17.68	11.84	15.69	11.10	18.13	15.28	12.40	20.58	17.35	14.07
Total per A/C	64.92	56.23	69.69	59.41	51.63	41.49	89.68	75.99	73.48	64.13	77.83	66.94	77.61	70.67	63.70	110.90	102.99	95.04
RNAV Reduction		13.4%		14.7%		19.6%		15.3%		12.7%		14.0%		8.9%	17.9%		7.1%	14.3%
Capacity	44.30	50.00	41.42	47.58	55.76	69.00	32.10	37.19	39.35	44.08	37.00	42.07	37.09	40.04	43.68	42.33	45.48	49.33
RNAV Increase		12.9%		14.9%		23.7%		15.9%		12.0%		13.7%		8.0%	17.8%		7.5%	16.5%

earlier part of this section, rather than the impact method used in the SRI analysis. That analysis was based on the assumption that multiple parallel RNAV routes could be used to eliminate overtake conflicts. This analysis is based on the assumption of a fixed RNAV route structure, with conflict workload reductions determined in earlier simulation studies. Also routine and surveillance benefits were identified, as discussed before.

The enhancement levels studied are Automated Data Handling (System 2), Automated Local Flow Control (System 3), Sector Conflict Probe (System 4) and DABS Data Link (System 6A). SRI also studied a modified data link environment (System 6B) where one-man sector teams were used, resulting in lower capacity but higher productivity. However, the capacities which resulted would probably not be sufficient to service traffic adequately based on traffic projections appropriate for the DABS/CMA implementation time frame. Therefore, System 6B was not considered in this analysis. The workload and capacity data which has resulted for the enhancement levels studied is summarized in Table 2.48. System 1A results are also stated in that table for comparison purposes. Note that System 2 and 3 results are identical. The data presented here is abbreviated; no values for total workload impact at a stated nominal traffic capacity demand level are given. This approach is used for purposes of brevity, since the critical items are the sector capacity values. Average RNAV impact is different for each enhancement level: 13.9% for System 1A, 14.5% for Systems 2 and 3, 14.3% for System 4, and 10.9% for System 6. Less impact is realized in a DABS/ CMA environment since many routine and conflict processing tasks are automated and so, at least partially, are removed from the controller's purview.

The sector capacity data is illustrated graphically in Figure 2.8. This shows bar charts for each of the seven sectors studied. A pair of bars is depicted for each UG3RD enhancement level (Systems 1A, 2 and 3 together, 4 and 6)

Table 2.48 RNAV Sector Workload and Capacity Impact, UG3RD Enhancement Levels 2, 3, 4 and 6

Seconds Per Aircraft

Sector Type	High Enrt.		Dep. Trans.		Departure		Arrival		Arr. Trans.		Low Arr.		Low Enroute			Low Enroute		
Sector ID	36		37		38		41		42		46		52			52		
Workload Limit	R-Controller		R-Controller		R-Controller		R-Controller		R-Controller		R-Controller		R-Controller			R/D Team		
RNAV Partic.	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%	50%	100%	0%	50%	100%
System 1A																		
Total Routine	30.74	26.68	37.86	31.49	40.47	31.12	58.49	49.70	40.35	37.20	41.05	35.17	47.34	43.39	39.44	103.30	98.54	93.78
Surveillance	25.00	24.60	26.25	25.83	15.00	14.76	23.75	23.37	22.50	22.14	26.25	25.83	17.50	17.36	17.22	17.50	17.36	17.22
Conflict Rate	0.324	0.228	0.284	0.201	0.028	0.018	0.418	0.277	0.442	0.296	0.424	0.300	0.490	0.413	0.335	0.490	0.413	0.335
Capacity	41.61	46.53	38.39	43.58	50.63	61.30	30.34	34.82	36.47	40.40	35.05	39.53	35.10	37.73	40.93	33.13	35.04	37.27
RNAV Increase		11.8%		13.5%		21.1%		14.8%		10.8%		12.8%		7.5%	16.6%		5.8%	12.5%
System 2,3																		
Total Routine	20.84	17.94	25.26	20.71	26.72	19.99	40.83	34.50	27.05	24.80	29.29	25.09	34.37	31.52	28.65	85.07	79.78	74.46
Surveillance	25.00	24.60	26.25	25.83	15.00	14.76	23.75	23.37	22.50	22.14	26.25	25.83	17.50	17.36	17.22	17.50	17.36	17.22
Conflict Rate	0.324	0.228	0.284	0.201	0.028	0.018	0.418	0.277	0.442	0.296	0.424	0.300	0.490	0.413	0.335	0.490	0.413	0.335
Capacity	47.13	52.77	44.83	50.76	66.10	79.60	36.14	41.52	42.22	47.27	39.78	44.76	40.23	43.17	46.79	38.16	40.95	44.34
RNAV Increase		12.0%		13.2%		20.4%		14.9%		12.0%		12.6%		7.3%	16.3%		7.3%	16.2%
System 4																		
Total Routine	20.84	17.94	25.26	20.71	26.72	19.99	40.83	34.50	27.05	24.80	29.29	25.09	34.37	31.52	28.65	85.07	79.78	74.46
Surveillance	25.00	24.60	26.25	25.83	15.00	14.76	23.75	23.37	22.50	22.14	26.25	25.83	17.50	17.36	17.22	17.50	17.36	17.22
Conflict Rate	0.239	0.162	0.211	0.144	0.018	0.011	0.282	0.184	0.303	0.200	0.315	0.215	0.346	0.289	0.231	0.346	0.289	0.231
Capacity	49.86	55.83	46.90	53.14	67.09	80.81	38.22	43.70	45.48	50.49	41.90	47.17	43.12	46.27	50.13	40.03	42.95	46.48
RNAV Increase		12.0%		13.3%		20.5%		14.3%		11.0%		12.5%		7.3%	16.3%		7.3%	16.1%
System 6A																		
Total Routine	16.96	15.06	21.98	18.72	20.88	16.47	32.52	27.53	23.50	21.85	26.36	22.50	31.46	28.83	26.19	77.42	73.02	68.61
Surveillance	25.00	24.60	26.25	25.83	15.00	14.76	23.75	23.37	22.50	22.14	26.25	25.83	17.50	17.36	17.22	17.50	17.36	17.22
Conflict Rate	0.134	0.103	0.118	0.092	0.011	0.007	0.164	0.114	0.175	0.124	0.176	0.137	0.197	0.171	0.146	0.197	0.171	0.146
Capacity	57.92	62.48	52.87	57.75	78.38	90.39	45.22	50.80	52.23	56.48	47.27	51.94	49.12	52.25	55.85	45.81	48.68	51.97
RNAV Increase		7.9%		9.2%		15.3%		12.3%		8.1%		9.9%		6.4%	13.9%		6.3%	13.4%

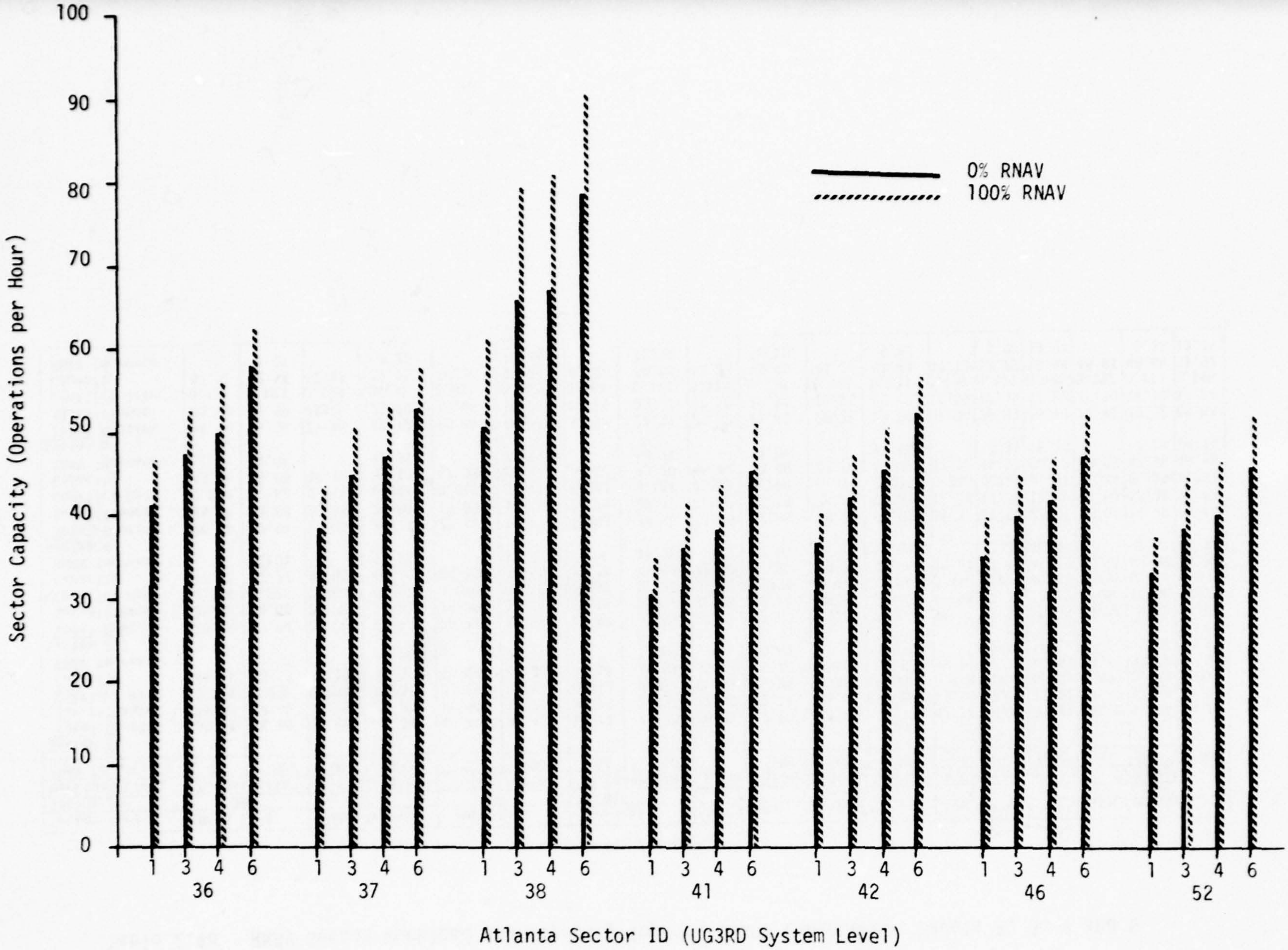


Figure 2.8 Sector Capacities Versus UG3RD System Level and RNAV Environment

at each sector. The solid bar is the no-RNAV case, while the shaded bar corresponds to the 100% RNAV case. As is apparent, the improvement from RNAV alone is usually equivalent to the improvement gained by advancing one step up in level of enhancement.

The sector which stands out in Figure 2.8 both in terms of initial capacity and, even more so, in terms of capacity growth resulting from the enhancements and RNAV, is sector 38 (Departures). The reasons are that conflicts are virtually nonexistent and that surveillance workload (which is unaffected by the enhancements) is small. This means that the significant reductions to routine workload due to the UG3RD enhancements and RNAV reflect directly as capacity increases and are relatively undiluted by the conflict and surveillance workload.

Area Capacity Impact and Staffing Implications

A methodology has been developed [5, 23] by which enroute center staffing requirements can be related to traffic demand and sector productivity improvements. This methodology includes selecting an area within a center for study which consists of several contiguous sectors. The routes traversing these sectors are modeled along with the traffic demand characteristics on each route, and sector capacities, using the Air Traffic Flow (ATF) network simulation model developed by SRI. The simulation is then exercised for increasing overall traffic demand rates, and enroute delays meted out for prevention of sector demands in excess of capacity are measured. Relationships of delay versus demand (such as illustrated in Figure 2.9) result. Staffing requirements are determined by first selecting the level of delay which is acceptable, and then determining the staffing required to achieve that level of delay for each value of traffic demand considered.

Added staffing (yielding corresponding capacity improvements) can be achieved in two ways: by adding to the number of positions at each sector (such as adding the Tracker position as mentioned earlier), or by splitting sectors. The additional capacity available from larger sector teams is limited, and essentially disappeared when UG3RD enhancements were added, according to the SRI studies. Therefore, sector splitting is more effective, although splitting a sector in two does not result in a doubling of the traffic capacity of the original area, since adding sectors involves increased intersector coordination and other routine A/G communications. In reference 5, sector splitting is used as the means to establish area capacity versus staffing relationships for the NAS Stage A base (System 1) case and for each of the UG3RD enhancements (Systems 2 through 6). A nine-sector area in the ATL vicinity was selected for study. The maximum capacity case studied was where each original sector was split, yielding eighteen sectors. All nine study sectors were in the high altitude airspace. Five of the sectors were taken from the original seven studied, while the remaining four were new. Their capacities were estimated by first presuming that, for each, the routine workload per aircraft would be equal to the workload computed for the original sector studied which was of like kind. Thus sectors 39 and 43 (arrival transition) were assigned the routine workload of sector 42, sector 40 (arrival) was given that of sector 41, and sector 44 (high enroute) was assigned that of sector 36. Surveillance workload values and conflict event frequencies were derived uniquely, and are presented in Table 2.49. The resulting capacity data are presented in Table 2.50.

Based on the capacities for these nine sectors as derived by SRI in reference 5, the ATF simulation was run for a series of traffic demand levels to establish delay/demand relationships, the results of which are illustrated

Table 2.49 Surveillance Workload and Conflict Frequencies, Sectors 39, 40, 43 and 44

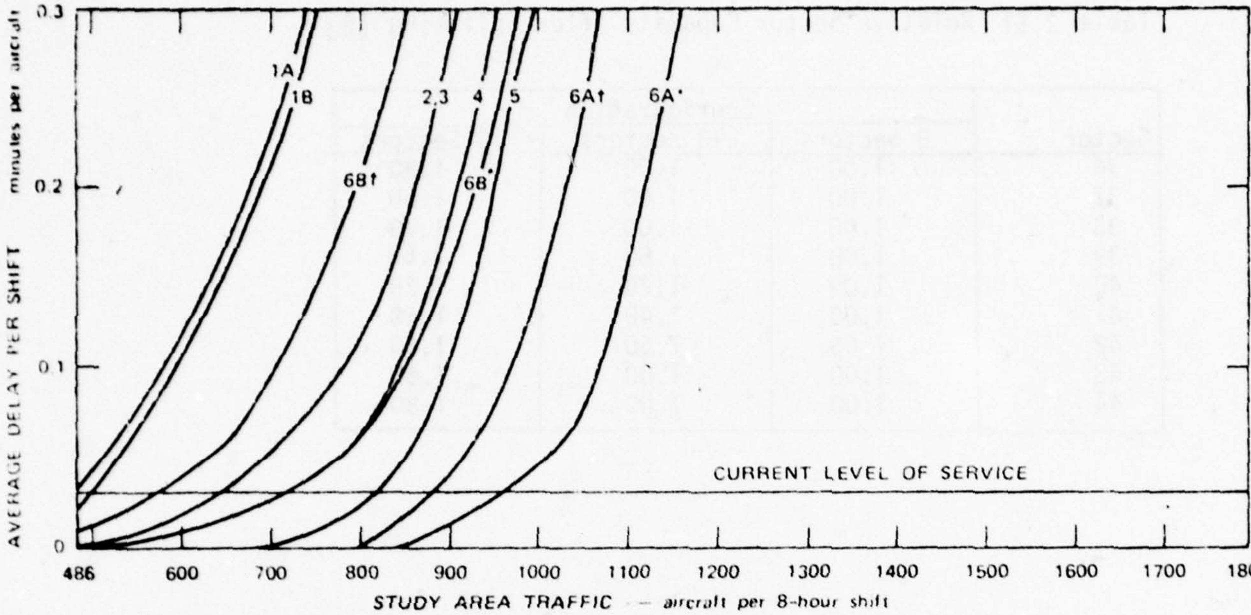
	Sector 39	Sector 40	Sector 43	Sector 44
Surveillance				
0% RNAV	17.50	15.00	17.50	26.25
100% RNAV	17.22	14.76	17.22	25.83
Conflicts				
Crossing:				
0% RNAV	1.7×10^{-3}	2.7×10^{-3}	4.6×10^{-3}	4.8×10^{-3}
100% RNAV	1.3×10^{-3}	2.1×10^{-3}	3.6×10^{-3}	3.8×10^{-3}
Overtake:				
0% RNAV	1.0×10^{-3}	5.8×10^{-3}	0.7×10^{-3}	1.5×10^{-3}
100% RNAV	0.6×10^{-3}	3.7×10^{-3}	0.4×10^{-3}	0.9×10^{-3}

Table 2.50 RNAV Sector Workload and Capacity Impact, Sectors 39, 40, 43 and 44

Sector Type	Arr. Trans.		Arrival		Arr. Trans.		High Enroute	
Sector ID	39		40		43		44	
Workload Limit	R-Controller		R-Controller		R-Controller		R-Controller	
RNAV Partic.	0%	100%	0%	100%	0%	100%	0%	100%
System 1A								
Total Routine	40.35	37.20	58.49	49.70	40.35	37.20	30.74	26.68
Surveillance	17.50	17.22	15.00	14.76	17.50	17.22	26.25	25.83
Conflict Rate	0.142	0.098	0.394	0.262	0.304	0.214	0.348	0.243
Capacity	44.85	48.66	33.26	38.62	40.97	44.97	40.51	45.34
RNAV Increase		8.5%		16.1%		9.8%		11.9%
System 2,3								
Total Routine	27.05	24.80	40.83	34.50	27.05	24.80	20.84	17.94
Surveillance	17.50	17.22	15.00	14.76	17.50	17.22	26.25	25.83
Conflict Rate	0.142	0.098	0.394	0.262	0.304	0.214	0.348	0.243
Capacity	55.00	60.11	40.19	46.81	48.56	53.80	45.72	51.23
RNAV Increase		9.3%		16.5%		10.8%		12.1%
System 4								
Total Routine	27.05	24.80	40.83	34.50	27.05	24.80	20.84	17.94
Surveillance	17.50	17.22	15.00	14.76	17.50	17.22	26.25	25.83
Conflict Rate	0.102	0.068	0.267	0.175	0.225	0.153	0.254	0.172
Capacity	57.17	62.27	42.82	49.69	51.34	56.79	48.48	54.24
RNAV Increase		8.9%		16.1%		10.6%		11.9%
System 6A								
Total Routine	23.50	21.85	32.52	27.53	23.50	21.85	16.96	15.06
Surveillance	17.50	17.22	15.00	14.76	17.50	17.22	26.25	25.83
Conflict Rate	0.058	0.043	0.155	0.108	0.126	0.098	0.143	0.109
Capacity	64.38	68.54	51.84	59.16	59.40	63.58	56.20	60.63
RNAV Increase		6.5%		14.1%		7.0%		7.9%

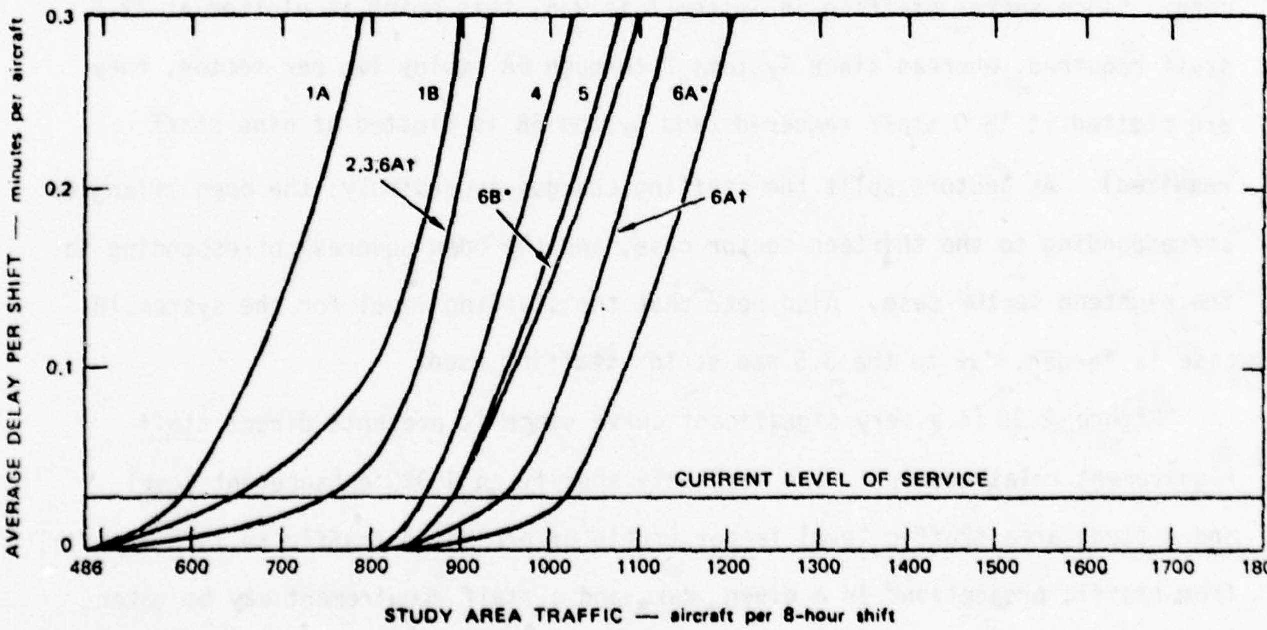
in Figure 2.9(a). Note that the SRI approach of including RNAV as a system level (5), and including those effects in System 6, produces delay results which are different from those which would be expected based upon the System 6 capacities derived herein. Figure 2.9 is included to illustrate the process used in reference 5 to determine staffing requirements. Figure 2.9(b) shows the shift in these curves when four of the nine sectors are split in two. The "current level of service" is that level achieved by System 1A at the present (1975) traffic demand level for this nine-sector area (486 A/C in an 8-hour shift). In the nine-sector case, System 2 crosses this line at about 710 A/C, indicating a gain in area capacity of about 46% due to System 2. In the thirteen-sector case (Figure 2.9(b)) System 2 crosses the line at about 750 A/C, indicating that the sector split gained about a 6% area capacity improvement. In the System 1A case, the sector split gained 21% (to 590 A/C), showing that the split has different effects depending upon the enhancement level.

The sector capacity gains due to splitting were estimated [5] for each sector in order to provide data from which Figure 2.9 could be created. These values are stated in Table 2.51. From this data, an average capacity value for the entire nine-sector area can be calculated from the original capacity data (Tables 2.48, 2.50) for the 13 and 18 sector (all nine sectors split in two) configurations. In reference 5 this process was carried one step further; sectors were split one-by-one and the simulation exercised for each case, producing the set of area staffing versus traffic growth curves reproduced in Figure 2.10. These are based on the constraint that the current level of enroute delays (as determined by simulation) would not be exceeded. The reader is cautioned again that System 5 is not included in the present analysis, and so



*100% data link aircraft
†50% data link aircraft

Figure 2.9(a) Delay/Traffic Relationships--Nine Sectors [5]



*100% data link aircraft
†50% data link aircraft

Figure 2.9(b) Delay/Traffic Relationships--Thirteen Sectors (Four Split)[5]

Table 2.51 Relative Sector Capacity After Splitting [5]

Sector	Configuration 9 Sectors	13 Sectors	18 Sectors
36	1.00	1.00	1.80
37	1.00	1.00	1.60
38	1.00	1.00	1.40
39	1.00	1.60	1.60
40	1.00	1.20	1.20
41	1.00	1.40	1.40
42	1.00	1.60	1.60
43	1.00	1.00	1.60
44	1.00	1.00	1.80

the 6A curves in Figure 2.10 illustrate capacity in excess of that derived in the present study. This situation will be corrected later.

In Figure 2.10, the open-circle points indicate the nine-sector (unsplit) case. Since sector staffing in System 1 is 2.5, this point is plotted at 22.5 staff required, whereas since Systems 2 through 6A employ two per sector, they are plotted at 18.0 staff required (and System 6B is plotted at nine staff required). As sectors split the staffing changes accordingly: the open triangles corresponding to the thirteen sector case, and the open squares corresponding to the eighteen sector case. Also note that the staffing level for the system 1B case is larger, due to the 3.5 man sector staffing used.

Figure 2.10 is a very significant curve since it presents direct staff requirement relationships. One need only specify an UG3RD enhancement level and a study area traffic level factor (ratio of projected traffic to 1975 traffic) from traffic projections in a given year, and a staff requirement may be taken off the curve. If the traffic factor is large enough to exceed the capabilities of the fully-split case (open squares), enroute delays would increase. The amount of increase could be estimated from curves like those shown in Figure 2.9.

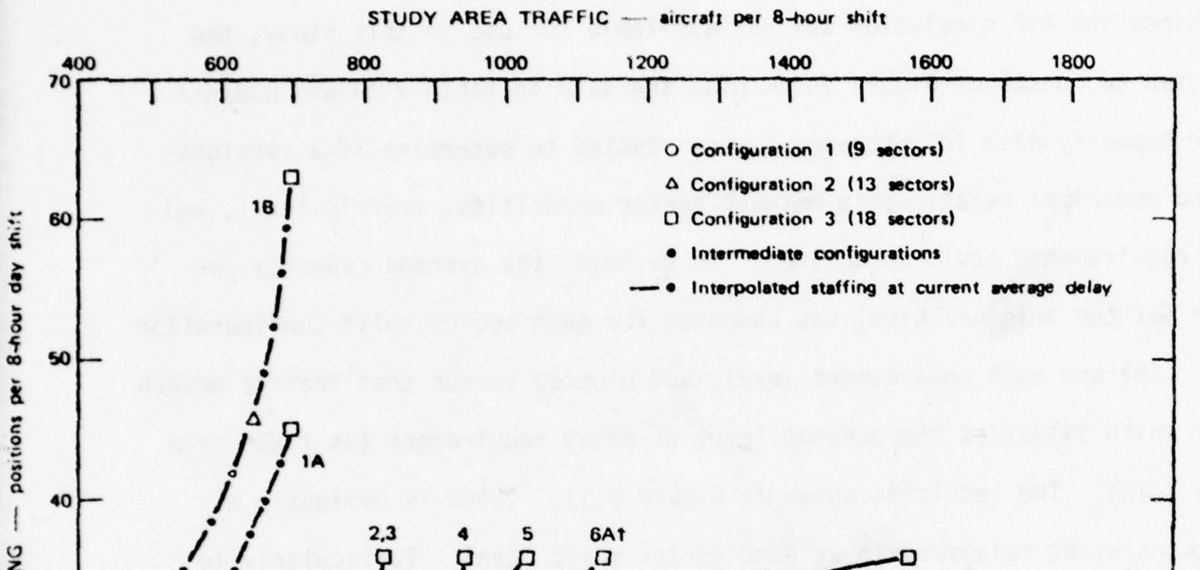


Figure 2.10 Study Area Staffing Relationships from Reference 5

It is of direct interest in the present study to modify Figure 2.10 to represent the cases studied; i.e. System 6A without the effects of the System 5 specified by SRI, and the effect of RNAV on each system (1A, 2, 3, 4 and 6A). Given this, the difference in staff requirement due to RNAV may be computed directly.

Since the ATF simulation was not available for use in this study, the data used to construct Figure 2.10, plus the data in Table 2.51 and nominal sector capacity data in reference 5 were studied to determine if a straightforward empirical relationship between sector capacities, traffic level, and staff requirements could be derived. To do this, the average capacity per sector (of the original nine) was computed for each sector split configuration (9, 13, 18) and each enhancement level, and plotted versus that traffic growth factor which satisfies the present level of delay requirement (as taken from Figure 2.10). The result is shown in Figure 2.11. There is obviously a quite consistent relationship at each sector split level. Particularly in the nine and thirteen sector configurations, all data points lie very close to the straight line which was least-square-fitted to the data. It is reasonable to expect a linear relationship between the traffic handling capacity of a multi-sector area and the average traffic capacity of the individual sectors, and so this result is not unexpected. In the eighteen sector configuration all points seem to be approximately in line except the 100% data link environment case. This case is discussed as being unusual in reference 5, although a satisfactory explanation of the cause is not offered. In order to accommodate this case, a piecewise linear fit is used for the eighteen sector case, with the breakpoint at a traffic level factor of approximately 2.25.

The relationships in Figure 2.11 were used to synthesize staffing relationships for enhancement system 6A (without the RNAV effects ascribed in reference 5) and for each of the systems (1A, 2, 3, 4 and 6A) with the full impact of RNAV as determined in this study, in the following manner for each

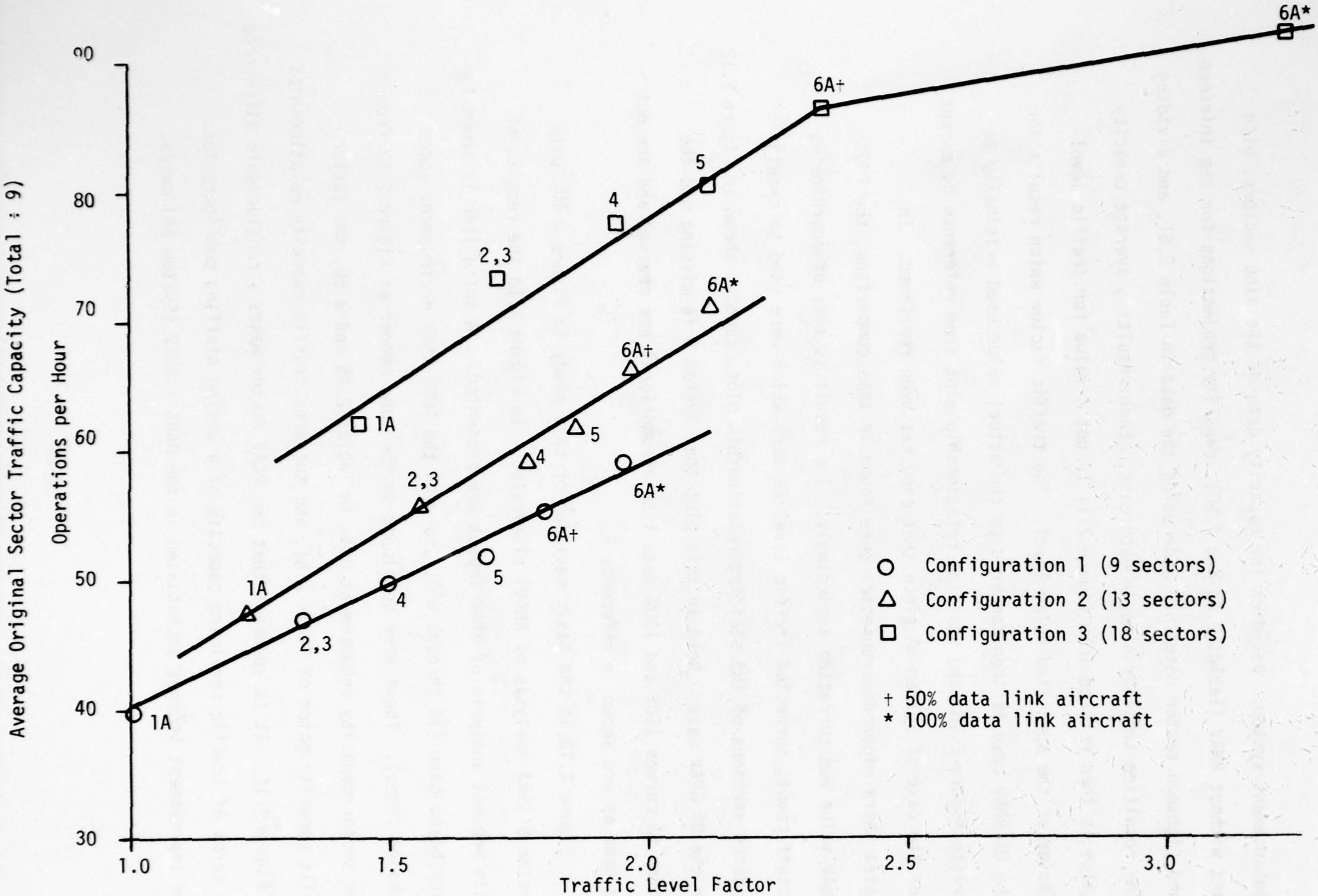


Figure 2.11 Study Area Sector Traffic Capacity Relationships

enhancement system: Based on the capacity data of the nine sectors, with and without RNAV (Tables 2.48 and 2.50), capacity projections for the thirteen and eighteen sector cases are made using the data in Table 2.51, and dividing the resulting total by nine in each case. Each resulting average capacity value is then entered into Figure 2.11 to get a value for traffic level factor at the specified delay level. The traffic factor which results for the 0% RNAV case is then compared to the actual value used originally to create Figure 2.10, the staffing relationship plot from reference 5, except for the case of System 6A since that case has been redefined. In cases where minor discrepancies were found in this comparison, the 100% RNAV value was corrected accordingly. The result is sets of coordinates (staff count, corrected traffic level factor) which were used to create updated versions of the staffing relationship plot, such as shown in Figure 2.12 for the 0% RNAV case. Note in this plot that System 5 is missing and the System 6A curves (50% and 100% data link assumptions) are revised and are not the same as are shown in reference 5.

Figure 2.12 is the basic revision of this study to Figure 2.10, with System 5 (SRI analysis of RNAV) eliminated. In Figure 2.13 the results of this present analysis of RNAV impact are presented. A solid line is shown for each basic case (1A through 6A), and with the 100% RNAV environment added (shaded lines). These were developed in the same manner as Figure 2.12 from the sector capacity enhancement data in Tables 2.48 and 2.50, the sector split capacity gains of Table 2.51, and the area traffic capacity relationships of Figure 2.11. It is apparent that the RNAV factor makes a considerable difference in terms of traffic servicing capacity of a giving staffing configuration. The improvement becomes accentuated in the DABS + RNAV (System 6A) cases.

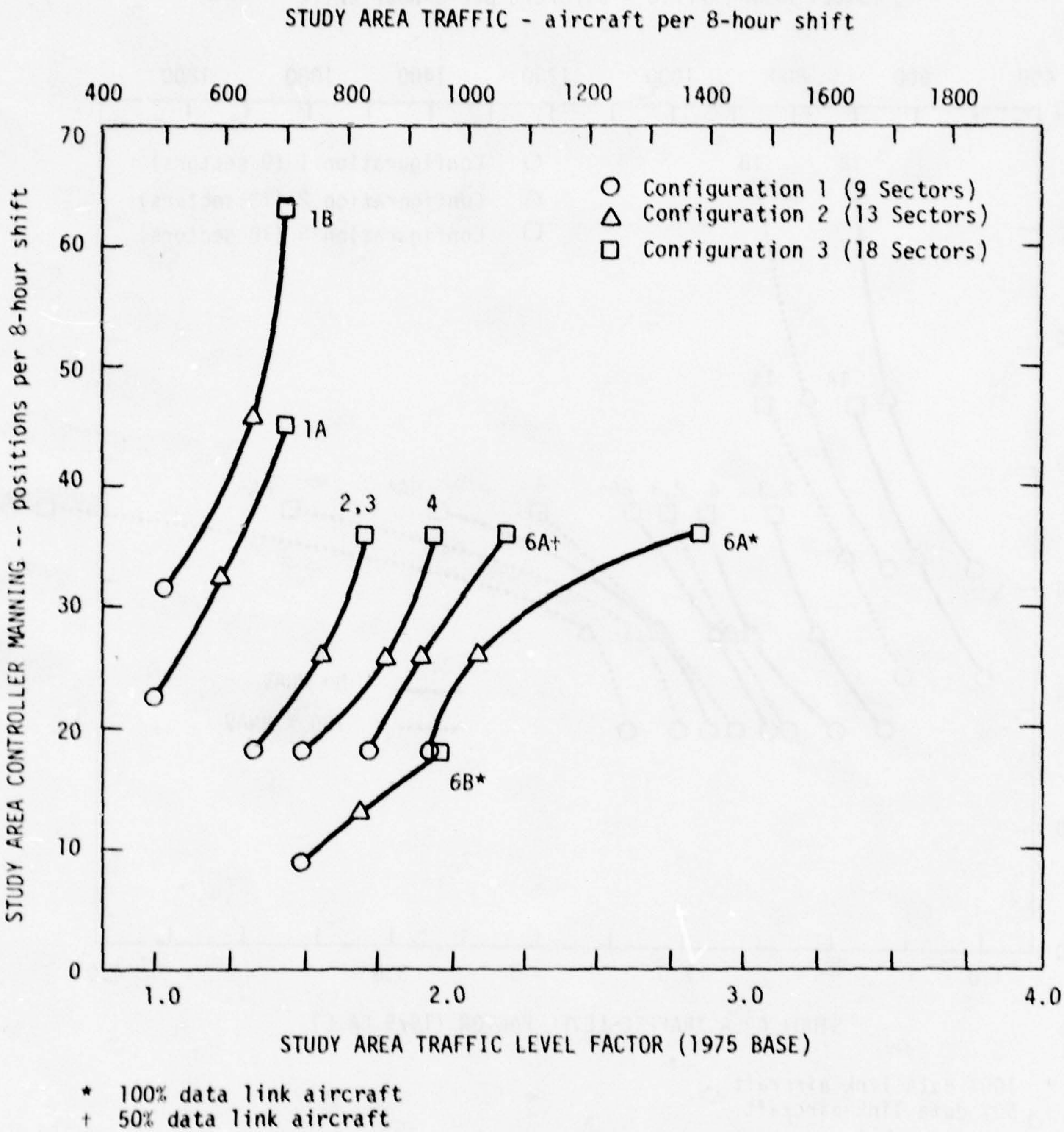
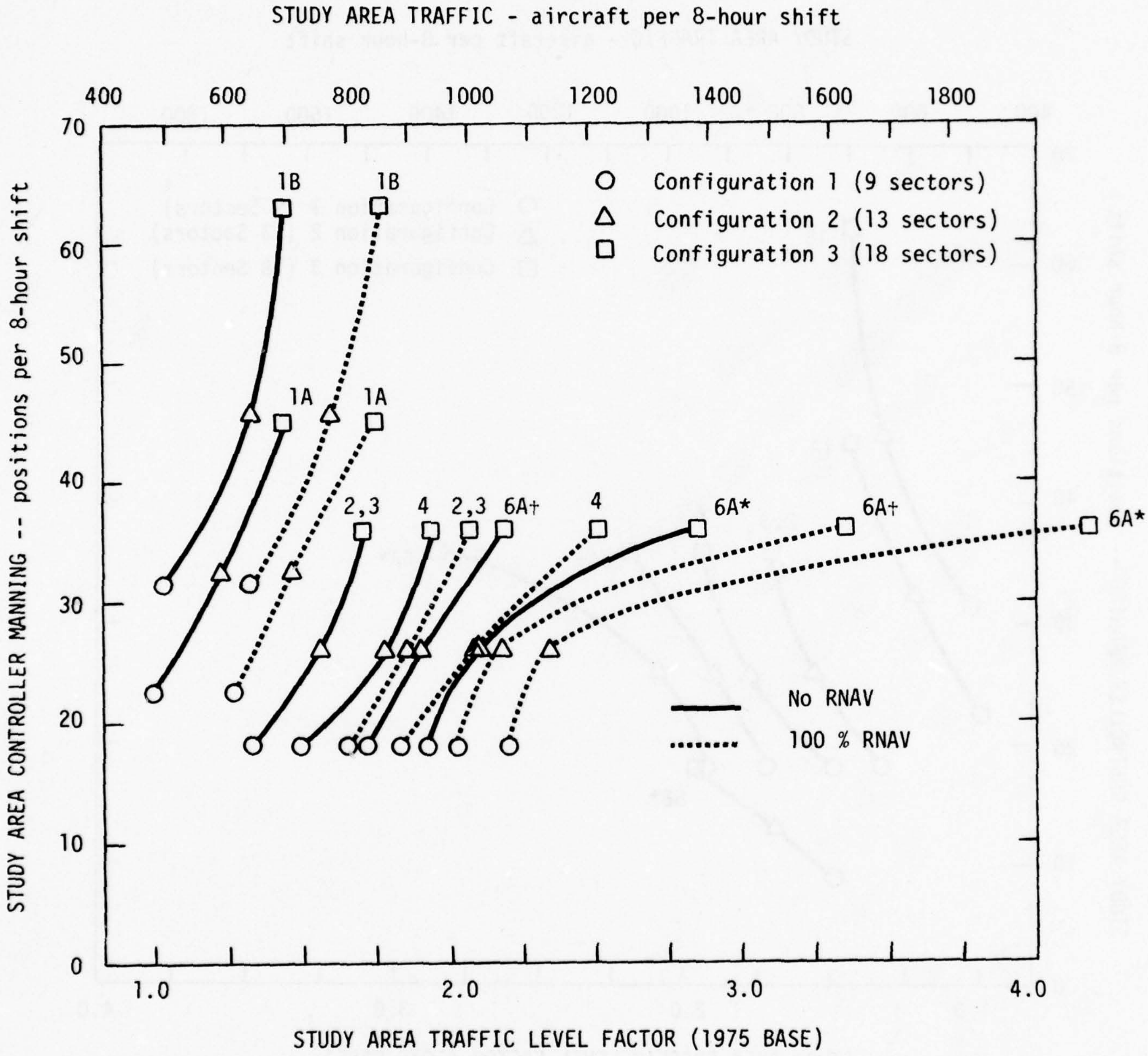


Figure 2.12 Study Area Manning Requirements: Revised with System 5 Eliminated



* 100% data link aircraft
† 50% data link aircraft

Figure 2.13 Study Area Manning Requirements as Affected by RNAV

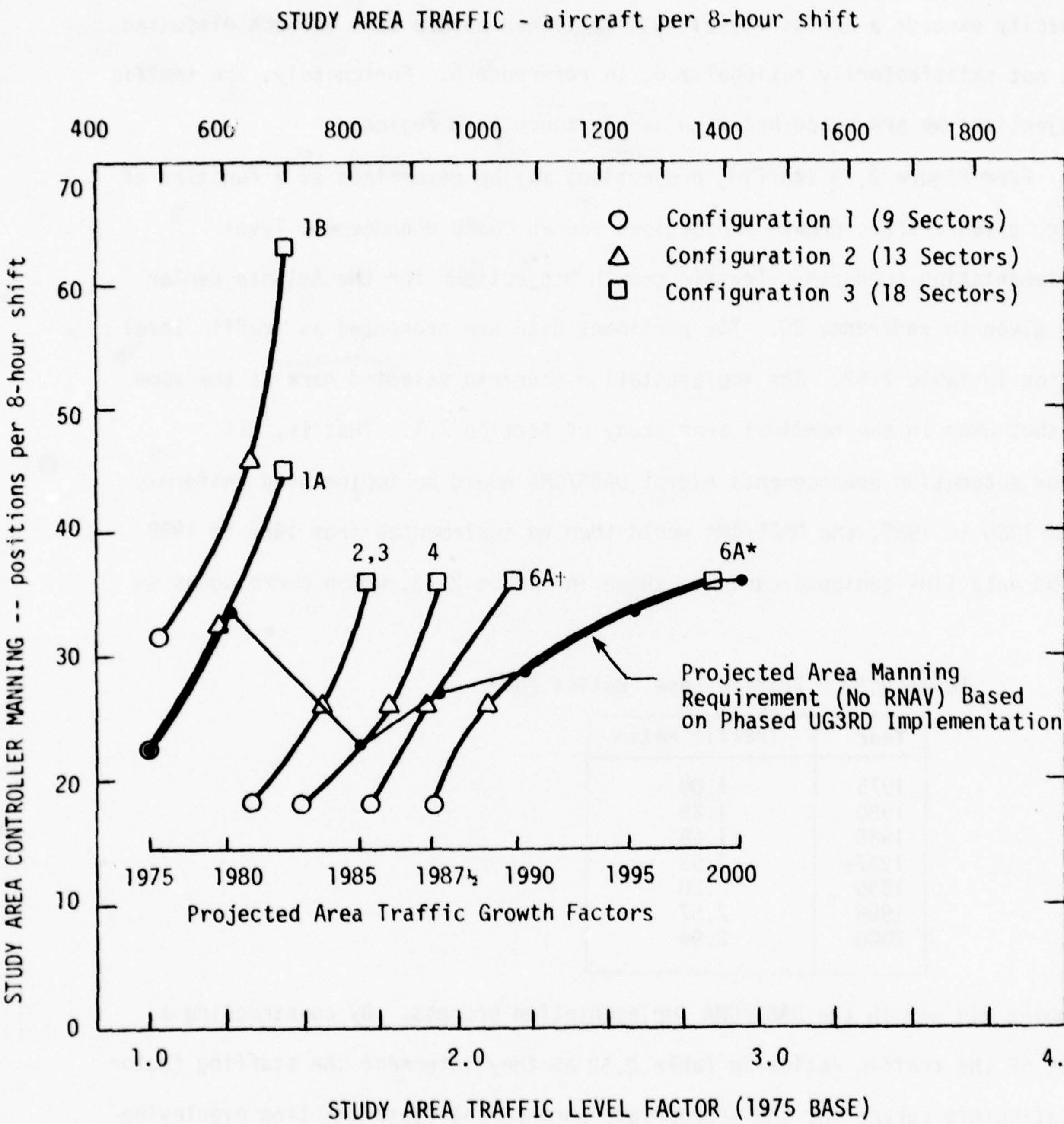
This effect, that of a non-linear improvement to area capacity when sector capacity exceeds a certain level, was mentioned before as a subject discussed, but not satisfactorily rationalized, in reference 5. Fortunately, the traffic projections we are concerned with barely touch this region.

From Figure 2.13 staffing projections may be determined as a function of year, given traffic growth projections and an UG3RD enhancement level implementation scenario. Traffic growth projections for the Atlanta center are given in reference 20. The pertinent data are presented as traffic level ratios in Table 2.52. The implementation scenario selected here is the same as that used in the terminal area study of Section 2.1. That is, all major automation enhancements except DABS/CMA would be implemented uniformly from 1980 to 1985, and DABS/CMA would then be implemented from 1985 to 1990. A 50% data link-equipped curve is shown in Figure 2.13, which corresponds to

Table 2.52 Traffic Level Ratios [48]

Year	Traffic Ratio
1975	1.00
1980	1.25
1985	1.68
1987½	1.92
1990	2.20
1995	2.57
2000	2.94

a point mid way in the DABS/CMA implementation process. By constructing a plot of the traffic ratios in Table 2.52 as they intersect the staffing factor relationship curves for the appropriate enhancement system, a line overlaying the curves in Figure 2.13 maybe drawn which represents required staffing as a function of time. This line, representing the 0% RNAV case, is illustrated in Figure 2.14 (thin solid line), with the traffic ratio points shown as large dots and the corresponding years listed directly below the curves. As may be seen from this curve, which represents the 0% RNAV case, staffing requirement rises



* 100% data link aircraft
+ 50% data link aircraft

Figure 2.14 Study Area Manning Requirements: Based on Traffic Growth Projections and Phased UG3RD Implementation

steadily until 1980 when automation features reduce the manpower requirement, resulting in a low by 1985. Subsequent to 1985, staffing climbs inexorably even though the DABS data link feature is being implemented. By 1990 data link is fully implemented and by 1998 or so no further sector splitting is possible, resulting in increases in enroute delays beyond that point.

In Figure 2.15 the phased staffing requirement curve is reproduced without the underlying system level curves. Also shown is the case presuming a reasonable RNAV implementation scenario, where RNAV implementation would begin in 1982 and be completely adopted by all transport aircraft (and nearly all high altitude aircraft) by 1985 (the sectors studied are all high altitude or high transition sectors). This is the scenario which was also used in the terminal area study (Section 2.1). From Figure 2.15 it can be seen that staff requirement savings (as indicated by the arrows) begin at a low level in 1982 and grow to 1985 where, by virture of RNAV capability, minimum sectorization is required (back to nine sectors). Until 1990, with RNAV implemented, no sector splitting at all would be required. Thereafter staffing requirements would follow the 100% data link + RNAV curve, yielding continuing significant staff savings up to (and beyond) the year 2000. Savings in 1985 are approximately 4.6 positions (20%), in 1990 are about 9.7 positions (34%), in 1995 are about 5 positions (15%) and 2000 are about 4.7 positions (13%).

2.2.2 Atlanta Center Staffing Implications

The staffing requirement situation expressed in Figure 2.15 represents the requirements of the nine-sector study area based on traffic growth projections for the entire Atlanta Center. Growth projections for the nine sectors alone were not available. However, for purposes of extrapolating the nine sector results to all forty Atlanta sectors, this is of no consequence.

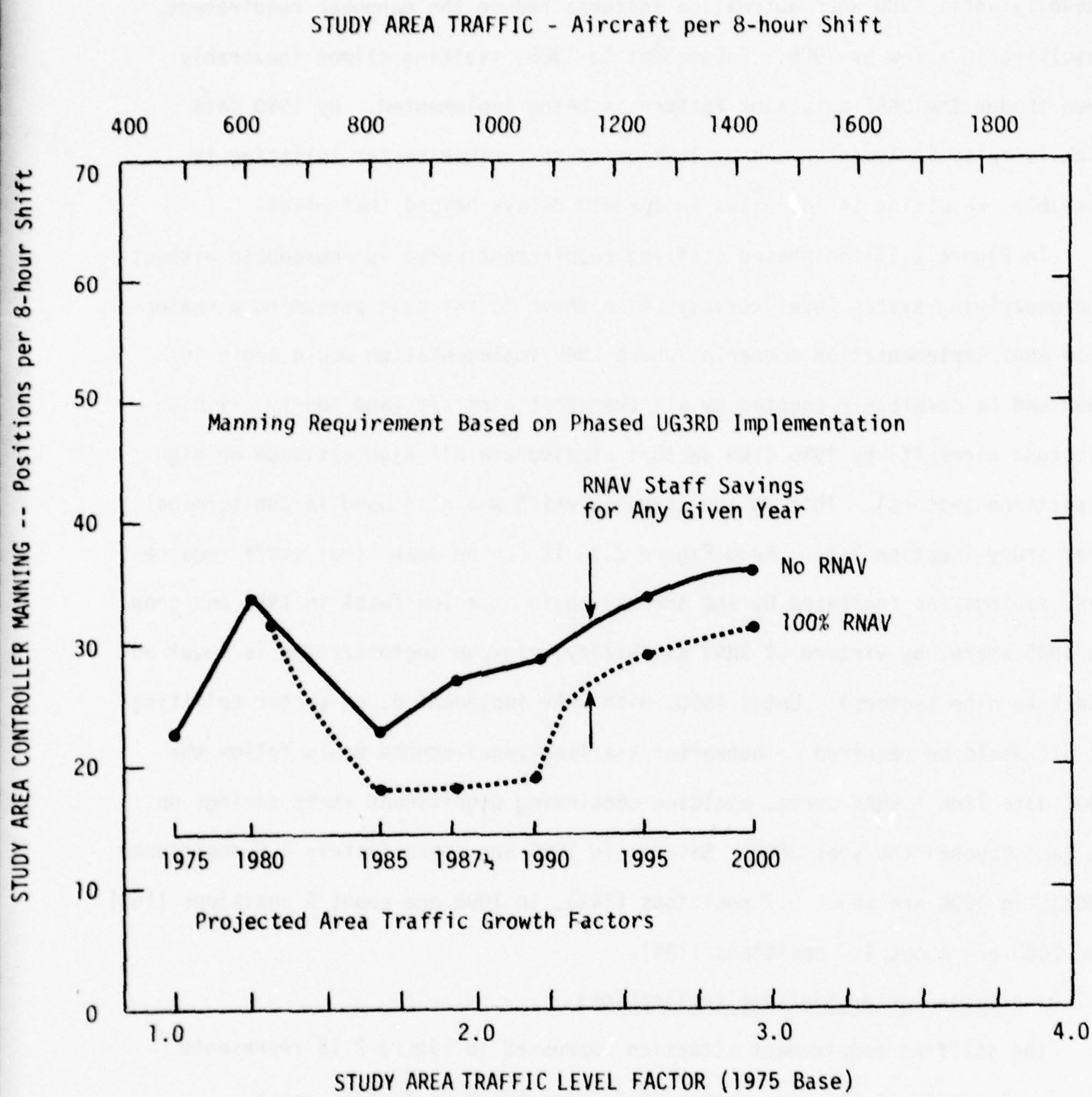


Figure 2.15 Study Area Manning Requirements Versus Time for Phased UG3RD Implementation With and Without RNAV

The only assumption required to extrapolate these results is that, in general, the remaining thirty-one sectors would on the average have staffing versus traffic growth relationships similar to Figure 2.15.

In the projection of staffing requirements, the 1976 calculated controller staffing for Atlanta center taken from the annual sector staffing printout for that year was used as the base number. Table 2.53 presents data taken from Figure 2.15, which is used for this extrapolation. That table lists the year, the traffic growth ratio from reference 20, the nominal nine-sector staff requirement at 2.5 men per sector (System 1A case for 1975), the staff savings due to RNAV, the RNAV benefit in percent, and the following other factors: Since the RNAV implementation scenario used to derive Figure 2.15 is based upon the assumption that 100% of transport aircraft would be so equipped by 1985, some allowance must be made for the GA aircraft, which would equip at a slower rate. It is assumed that only a maximum of 50% of GA aircraft would equip, and would do so over the same schedule time period. Based on the traffic projections in reference 20, which separately states transport and GA traffic counts for each year, a benefit dilution factor may be computed which accounts for the relative amount of GA traffic. This is used to modify the RNAV benefit value to account for non-RNAV equipped GA aircraft. These factors are all listed in Table 2.53.

In order to project the RNAV benefit for the entire Atlanta center, the 1976 calculated controller staffing value (476) was assumed to be representative of 1975 staffing and was multiplied by the staff growth factors and net RNAV benefit factors in order to get the staff savings projection for each year of interest. Values for intervening years were arrived at through interpolation. These results are presented in Table 2.54, which shows annual controller staff

projections as well as savings. Total staff man-years and RNAV savings man-years are listed at the bottom of the table. Over the nineteen year

Table 2.53 RNAV Impact Adjusted for 50% GA Equipage Factor

(Phased implementation of UG3RD Features Presumed)

Year	Traffic Ratio	Staffing Ratio	9-Sector Staff	RNAV Savings	Percent Savings	Benefit Dilution	Net Benefit
1975	1.00	1.00	22.5	—	—	.7833	—
1980	1.25	1.50	33.7	—	—	.7766	—
1982	1.40	1.32	29.6	2.25	7.60%	.7593	5.77%
1983	1.47	1.24	27.9	3.83	13.73%	.7514	10.32%
1984	1.54	1.16	26.2	4.80	18.32%	.7454	13.66%
1985	1.68	1.01	22.7	4.63	20.40%	.7377	15.05%
1987½	1.92	1.19	26.8	8.73	32.57%	.7232	23.55%
1990	2.20	1.27	28.5	9.75	34.21%	.7102	24.30%
1995	2.57	1.50	33.8	5.05	14.94%	.7014	10.48%
2000	2.94	1.60	36.0	4.70	13.06%	.6933	9.05%

period RNAV is in use, an overall savings of 1691 man-years, or 14.5%, is realized.

In reference 5 the sensitivity of other facility staffing groups to overall traffic level was studied. It was found that position requirements for team supervisors, area officers and area specialists are directly affected by major changes in traffic level, since their requirements are in direct proportion to the number of sectors manned. The average proportionality constant relating these staff to controller staff level is approximatley 11%; therefore, RNAV benefits would also increase by that amount in terms of actual man-years saved.

Table 2.54 Annual Atlanta Controller Staff and RNAV Savings

Year	Baseline Staffing	RNAV Savings
1975	456	—
1980	684	—
1982	602	35
1983	565	58
1984	529	72
1985	461	69
1986	494	93
1987	527	116
1988	550	131
1989	565	136
1990	579	141
1991	600	127
1992	621	113
1993	642	100
1994	663	86
1995	684	72
1996	693	71
1997	702	70
1998	712	68
1999	721	67
2000	730	66
TOTAL (man-years)	11640	1691

2.2.3 Impact Projections Over All Centers

Impact projections over all ATC centers follow the same procedure as expressed in the previous section. However, a new relationship of staff requirements versus time must be derived since nationwide traffic growth patterns are not identical to that pattern specific to the Atlanta center. Therefore, a new set of relationships shown in Figure 2.16 have been created which are based on national traffic growth projections taken from reference 20. These projections, and the resultant staffing data are given in Table 2.55. The RNAV savings percentages which have resulted were applied to the baseline (1976) controller staffing level for all twenty centers (7656 controllers), with the results

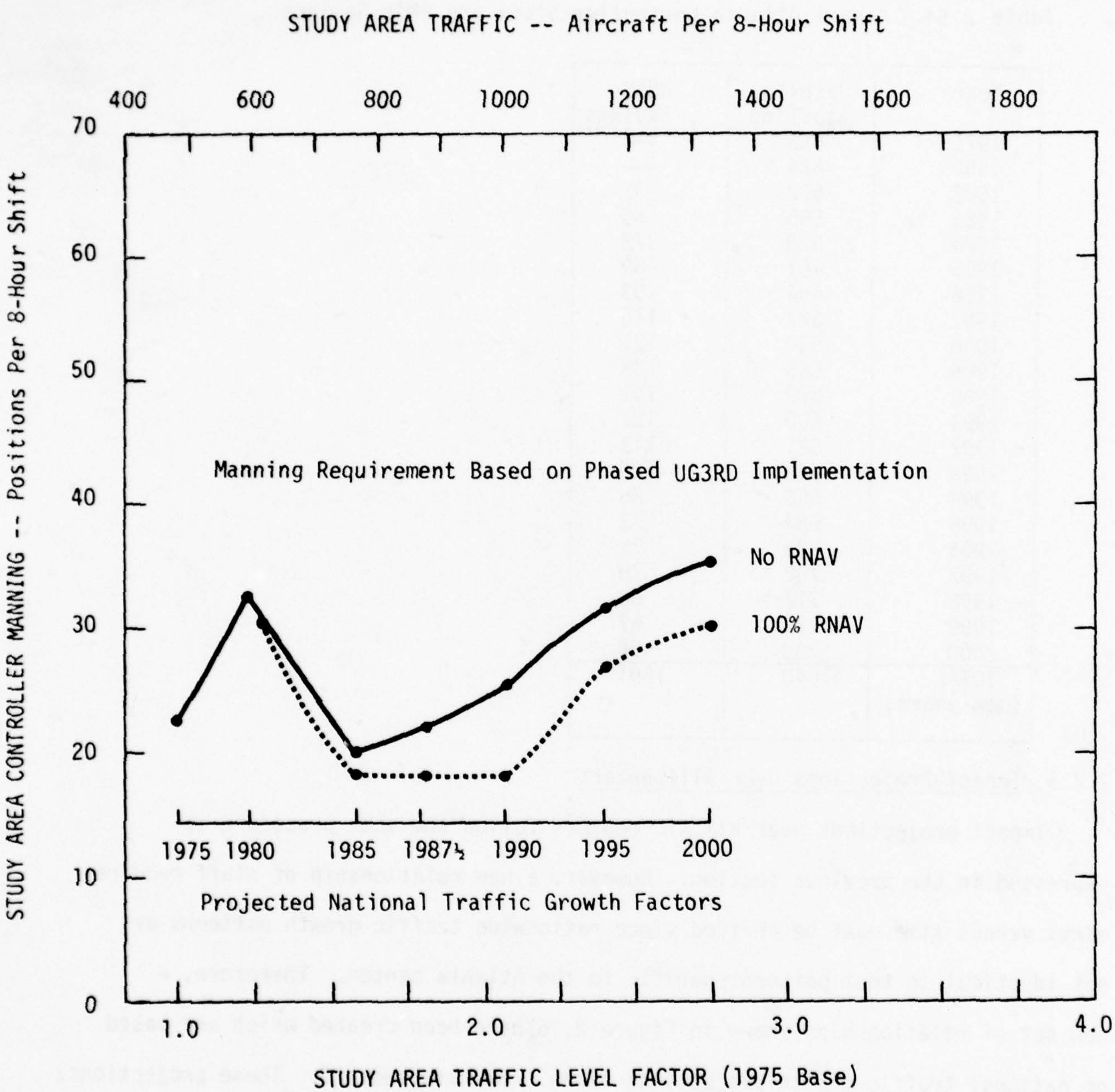


Figure 2.16 Study Area Manning Requirements for National Traffic Projections, With and Without RNAV

Table 2.55 National RNAV Staffing Requirements Impact

(Phased implementation of UG3RD features presumed)

Year	Traffic Ratio	Staffing Ratio	9-Sector Staff	RNAV Savings	Percent Savings	Benefit Dilution	Net Benefit
1975	1.00	1.00	22.5	—	—	.7633	—
1980	1.22	1.44	32.5	—	—	.7584	—
1982	1.36	1.24	27.8	1.50	5.39%	.7425	4.00%
1983	1.43	1.11	24.9	2.75	11.05%	.7357	8.13%
1984	1.49	1.01	22.7	2.63	11.61%	.7295	8.47%
1985	1.57	0.88	19.8	1.83	9.23%	.7227	6.67%
1987½	1.79	0.96	21.7	3.73	17.19%	.7091	12.19%
1990	2.06	1.12	25.2	7.18	28.51%	.6965	19.86%
1995	2.40	1.41	31.7	4.90	15.48%	.6888	10.66%
2000	2.74	1.57	35.3	5.18	14.70%	.6811	10.01%

presented in Table 2.56. The total RNAV savings over the nineteen year period nationwide would be 20,498 man-years, or 11.1% of total controller staffing requirement. The 1976 present value equivalent savings at a 10% discount rate would be $121.34 million, at a 1975 wage and benefits rate of $24,795 per man-year. As stated in the previous section, this savings should be inflated by 11% to account for savings in other demand-sensitive ATC center staff positions.

Table 2.56 National RNAV Staffing Requirements Impact

Year	Baseline Staffing	RNAV Savings
1975	7656	
1980	11059	—
1982	9476	379
1983	8466	689
1984	7707	653
1985	6744	450
1986	7000	630
1987	7256	810
1988	7621	1060
1989	8094	1381
1990	8568	1702
1991	9008	1591
1992	9448	1480
1993	9889	1370
1994	10329	1259
1995	10769	1148
1996	11014	1158
1997	11259	1169
1998	11504	1179
1999	11749	1190
2000	11994	1200
Total (Man-Years)	185279	20498
1976 Present Value Savings: $121.34M		

3.0 TRAFFIC CAPACITY AND DELAY IMPLICATIONS

3.1 EFFECTS OF RNAV ON AIRPORT CAPACITY

In this section the mechanisms whereby RNAV can improve airport arrival and departure capacities, and therefore reduce delays, are explored. Section 3.1.1 discusses these various effects, while the later sections present a methodology for evaluating the arrival delay benefit and a computation of the benefits which result. No data sources were located which would serve to quantify a tangible departure capacity improvement or delay savings result, and so no departure results are presented.

3.1.1 Potential for Airport Capacity Improvement

There are two primary sources of arrival capacity improvement potential which can result through the application of RNAV techniques. In the first place RNAV allows arriving aircraft to be spaced more accurately and uniformly, since the controller is relieved of routine navigation duties and may center his attention on the final approach sequencing area of his sector. This RNAV capability was conclusively demonstrated in the most recent real time simulation study conducted at NAFEC [9]. That study showed an overall arrival capacity improvement under dense traffic situations of 3.26% due to RNAV. The other source of arrival capacity improvement available from RNAV results from the accurate time control capability available in the form of the 4D RNAV function. In a Metering and Spacing environment configured to be compatible with 4D RNAV-equipped aircraft, the time control feature enables reduced in-trail separations due to the use of the more accurate control technique which 4D provides. As discussed in detail in reference 1, the 4D delivery accuracy is projected to be 5 seconds (1σ), as opposed to 8 seconds for an automated M&S system without 4D capability. The reduction to in-trail separation which will result will translate into increased operations rates. This is especially important since an M&S system which is not 4D-compatible, while improving overall operations rate when compared to the manual

environment, eliminates the beneficial impact which RNAV has been shown to provide in the manual environment.

Regardless of the source of airport arrival capacity improvements, the result is a decrease to overall arrival delays. Often the delay reduction can be dramatic for only a minor improvement to capacity. This is true at airports where demand is (or is projected to be) in excess of capacity for a significant fraction of each day, or is greatly in excess of capacity for shorter periods. Airports where the demand is (or is projected to be) adequately served have small average delays, and so would be benefitted little by capacity improvements. An objective of this analysis is to quantify the reductions in delay to be expected due to RNAV at the major airports over the period of years to 2000, considering the projected growth in traffic at those airports and presuming an orderly implementation of RNAV and the other UG3RD features.

As operators at dense terminal areas become RNAV equipped, airport departure capacity may also increase. The causes of these potential improvements are related to the enroute, as well as terminal, environments. As discussed in detail in Section 2.2, RNAV will cause significant reductions to enroute controller workload and thereby allow improved sector capacity. This is particularly true with respect to transition sectors since RNAV will reduce conflicts to a large degree. Also, a well-designed transition/enroute RNAV route structure should be able to provide increased routing capacity. Therefore, at the denser airports where the ability of the transition/enroute sectors to absorb traffic limits departure runway operations, RNAV could result in departure capacity improvements and, therefore, reductions to ground delays.

Ground departure delays might also be reduced through the ability of RNAV to improve arrival runway operations rate. First of all, improved arrival capacity will result in faster service to the arriving aircraft. This will lessen the competition for available runways between arrival and departure operations, resulting in a benefit of some form at airports where one or more runways are

used for mixed (arrival/departure) operations. Also, better control over spacing should allow a better facility for mixing departure slots in amongst the arrival traffic. Airports with dedicated arrival and departure runways would not be so affected. An improved arrival capacity at high density airports will tend to reduce departure delays at all airports originating flights to such airports, through action of the flow control system. The flow control system, through issuance of Fuel Advisory Departure notifications, tends to cause aircraft to absorb part of the expected arrival delay on the ground prior to departure, thus conserving fuel as well as expenses. Thus arrival capacity improvements can reflect into departure delay reductions even though departure runway capacity may be unaffected.

Unfortunately, there are no data sources available which can be used to directly quantify the capacity improvements or delay reductions anticipated in the departure case. The recent NAFEC real time simulation, as described in reference 9, modeled departing aircraft, but considered departures to be independent of arrivals, and did not attempt to model the transition/enroute departure sectors and all of the conflicting traffic which would exist in those sectors. Therefore, a zero impact on departure rate was measured. In the enroute RNAV fast time simulation study [25]discussed in Section 2.2, transition and enroute structures were modeled, but no attempt to determine sector capacities was made. In the SRI enroute studies [5,22]sector capacities are determined, as affected by the several UG3RD enhancement features, but no attempt was made to relate transition sector capacity to airport departures or delays. Rather, delays were held constant as the controlling factor, while sectors were split to achieve the necessary capacity. Therefore, in this study no quantification of departure delay savings due to RNAV can be made.

In the NAFEC real time RNAV simulation study, capacity was determined through measuring the time required for a fixed set of aircraft to be serviced. As mentioned in Section 2.1, this is accomplished by designating a large sample

of "key" flights, the first of which arrives in the terminal area after sufficient traffic has arrived to fully load the system. The capacity is then determined by measuring the traffic landed and the time interval between the first and last key flights. This technique effectively standardizes the process of measuring many parameters besides capacity by eliminating most sources of random variations. The results of multiple simulations with varying mixes of RNAV and conventional aircraft were processed to determine RNAV impact and level of significance. The arrival capacity impact was found to be 3.26% at a confidence level of 95%, while no statistically significant impact on departure capacity was found. It should be stressed that this impact was determined under a simulated busy period; e.g., demand was sufficient to saturate the system. Therefore, the capacity impact identified applies only during busy periods. Arrival delays were also measured in the simulation. Delays for key flights were found to be diminished by 34% in a 100% RNAV environment, dropping from 15.0 minutes per aircraft to 9.8 minutes. Departure ground hold delays were not affected. Since this measurement for delay savings is applicable only to the New York JFK environment simulated, the 34% delay reduction measured cannot be extrapolated to other terminal areas directly. However, it is indicative of the degree of savings available in an RNAV environment.

It should perhaps be mentioned that any system improvement which provides an arrival capacity improvement of 3.26% would, in general, have resulted in an equivalent delay savings. The delay benefit results not directly from RNAV but from the capacity improvement caused by RNAV usage. Therefore, should some other UG3RD enhancement feature increase capacity at an airport, the RNAV capacity improvement would cause a lesser delay benefit than would have been the case had the UG3RD enhancement not come into play. Consideration of the other UG3RD enhancements is included in the calculation of RNAV delay savings benefits in Section 3.2.

The benefit in terms of capacity improvement demonstrated in the NAFEC simulation of 2D and 3D RNAV systems would tend to disappear in a Metering and Spacing environment. In reference 1, M&S with and without RNAV was analyzed in detail in order to compare system performance with and without RNAV. Both arrival gate delivery error and controller workload factors (see Section 2.1.1) were analyzed. No particular improvement by RNAV to the M&S gate delivery accuracy was demonstrated. Therefore, once M&S is installed and operating at an airport, the incremental capacity benefit resulting from basic 2D or 3D RNAV capability disappears. However, if the M&S software is configured to accommodate 4D RNAV capability and take advantage of the higher gate delivery accuracy available through the usage of 4D RNAV, the situation changes dramatically.

In reference 1 analysis is presented which shows that, while Metering and Spacing in a radar vector or RNAV environment can yield a gate delivery error of approximately eight seconds, the usage of 4D RNAV procedures will drop this error to 5 seconds. The level of error is important since it defines the separation buffer which must be provided over and above absolute minimum separation in order to prevent these errors from resulting in violations of minimum separation more than a specified percentage of time (e.g., 5%). As discussed in reference 26, the corresponding error in the present manual environment is approximately 18 seconds. The error values stated are 1σ values. In order to assess minimum separation violation probability, these 1σ values must be converted to buffer sizes corresponding to specified violation probabilities. These conversion factors are 1.69σ and 2.33σ for violation probabilities of 5% and 1% respectively. According to reference 26, the 5% figure is appropriate to a basic M&S environment, while highly automated ATC features with reduced in trail separations afforded by WVAS and other features should have the further protection of the 1%

violation probability. While this may well be good practice, it presents a complicating factor in the analysis of the impact of 4D RNAV on capacity and delay. In the following paragraphs an analysis is performed to derive a single 4D capacity improvement percentage value (based on a 5% probability) which is representative of most large airports, rather than to calculate the actual 4D impact to be expected at each and every airport considered. Expression of the capacity (and therefore delay) impact of 4D given a 1% violation probability would require estimating the time-phasing period over which transition to the 1% probability would be required, and will also yield even larger 4D benefit values than would the 5% assumption. Therefore, to simplify the procedure while remaining conservative in estimating benefits, the 5% violation probability is used throughout the analysis.

In order to estimate an average, representative 4D capacity improvement percentage, several airports were selected as examples for analysis. The capacity analysis procedure used is that defined by Harris [27] in which many pertinent factors are considered: Minimum longitudinal spacings as a function of aircraft size class (the 3/4/5 mile criteria was used here); aircraft type class percentage breakdowns; approach speeds typical of each type class; and minimum separation violation prevention buffer sizes (1.69 x 1σ gate delivery error). This capacity methodology is further explored and applied in an earlier 4D benefit analysis in reference 2. This analysis has been applied to several airports given 1985 traffic aircraft type mix projections from reference 20. Final approach speeds for each aircraft type category are developed in reference 2. Based on these data, the arrival runway capacity per arrival runway with and without 4D in an M&S environment (5 sec. versus 8 sec. control precision) have been computed for five high density airports, the results of which are presented in Table 3.1. Also shown in that table are the ideal capacities given perfect control precision. The 4D improvement, in percentage terms, is listed in the

Table 3.1 Estimated 4D Arrival Capacity (per runway) Improvement in a Metering and Spacing Environment

AIRPORT	CAPACITY ESTIMATE			
	M&S	M&S + 4D	PERFECT	4D IMPROVEMENT
Chicago O'Hare	36.8	38.5	41.4	4.6%
La Guardia	38.5	40.5	44.0	5.1%
Denver	38.1	40.0	43.4	4.9%
Miami	36.3	37.9	40.6	4.4%
San Francisco	39.5	41.3	44.2	4.5%

last column. The improvement ranges from 4.4% to 5.1% for the five airports examined, and so a value of 4.6% was selected as representative for purposes of extrapolation to a larger set of high delay airports. The usage of the 3/4/5 mile minimum separation criteria is expected to produce conservative results as separations are eventually reduced due to implementation of WVAS and other features. As minimum separation criteria decrease, the impact of the constant 4D buffer size reduction increases in terms of the percentage of capacity. Therefore, since minimum separations are projected to decrease, the assumption used will produce a conservative estimate of 4D impact on capacity.

3.1.2 Arrival Delay Savings Projection Methodology

In order that an increase in capacity at an airport can be translated into the reduction in delays which would result from such an increase, three things must be known: the existing (or projected) traffic at the airport and its peaking factor; the present (or projected) level of delay experienced by the traffic; and a relationship describing the effect of changes in capacity on delays experienced. Projections of traffic demand at airports are readily available from reference 20, and historic peaking factors are also available (reference 28, among others). However, reliable data describing projected delays, given an orderly implementation of UG3RD programs, has not been available for use in earlier analyses of 4D RNAV delay savings benefits (References 1 and

2. These early analyses relied upon a model of the delay relationship to airport capacity, traffic hourly demand pattern and overall traffic level which did not consider:

1) Changes in airport capacity due to projected physical airport improvements, and
2) Changes in airport capacity due to the implementation of UG3RD features.

Recognizing these deficiencies, these earlier studies did not attempt to project delays and delay savings to the year 2000. Rather, a 4D delay benefit (per aircraft) was developed for a few airports for the year 1985. This benefit was extrapolated to 25 airports, and assumed to remain constant to the year 2000.

The present analysis is based on detailed studies of airport capacities at thirty airports as UG3RD features are implemented (reference 29) and a projection of delays which will result from the capacities of reference 29 given recent traffic growth projections (reference 28). The latter study presents delay projections to the year 2000 for three ATC scenarios:

1) Continuation of the existing ATC environment (base case)
2) Near-term UG3RD improvements (manual WVAS, basic M&S, automatic data handling)
3) Total UG3RD environment (automated WVAS, advanced M&S, data handling, conflict resolution, CMA, DABS, IPC)

This breakdown is roughly equivalent to the breakdown used in Section 2.1 (levels 1 (ARTS III), 4 (ARTS III + AFDH + M&S + CP) and 6 (level 4 + DABS + CMA)), so the same implementation schedule can be used here. That is to say that the near-term improvements will be phased in from 1981 to 1985, and the remaining UG3RD features will be phased in from 1986 to 1990.

One problem which exists when applying the delay projections of reference 28 to this study is that the traffic projections used in generating that delay data were slightly different than those [20] which are to be used for this study. However, it was found from experimentation that a quadratic least-squares curve fit produced a very accurate fit of projected delays as a function of projected traffic growth in nearly all cases. Thus, curve-fitting was used to generate delay values for the new traffic projections taken from reference 20. As a check, the RMS error of each data fit was computed, and in most cases amounted to just a few percent of the delay values given.

New sources of delay/capacity relationships are available since the studies of 4D benefits in references 1 and 2 were conducted. References 30, 31 and 32 are a set of reports which provide detailed procedures for estimating airport capacity and projecting delays based upon detailed analyses of airport facilities. The delay relationships presented in those reports are quite complex, and are oriented towards analyzing delays for specific airport configurations and demand patterns. However, it was necessary to avoid highly detailed analysis due to the limited scope of this study. Also, the baseline delay projections having been already completed and presented in reference 28, all that is necessary are relationships describing the sensitivity of delay to small changes in capacity. Simpler, more general delay/demand/capacity relationships are presented in reference 33. These relate delay to absolute capacity, demand, peaking factor and overall demand pattern. Demand patterns are resolved into three categories of daily behavior: no peak (or a very broad peak), one peak and two (roughly equal) peaks of demand. For purposes of convenience, the one-peak case was assumed to be representative for all airports. The delay savings for small capacity improvements are not much different for the other two patterns, and so the results are not significantly affected. An example set of curves from reference 33 is shown in Figure 3.1.

The basic delay impact computation procedure is straightforward, although

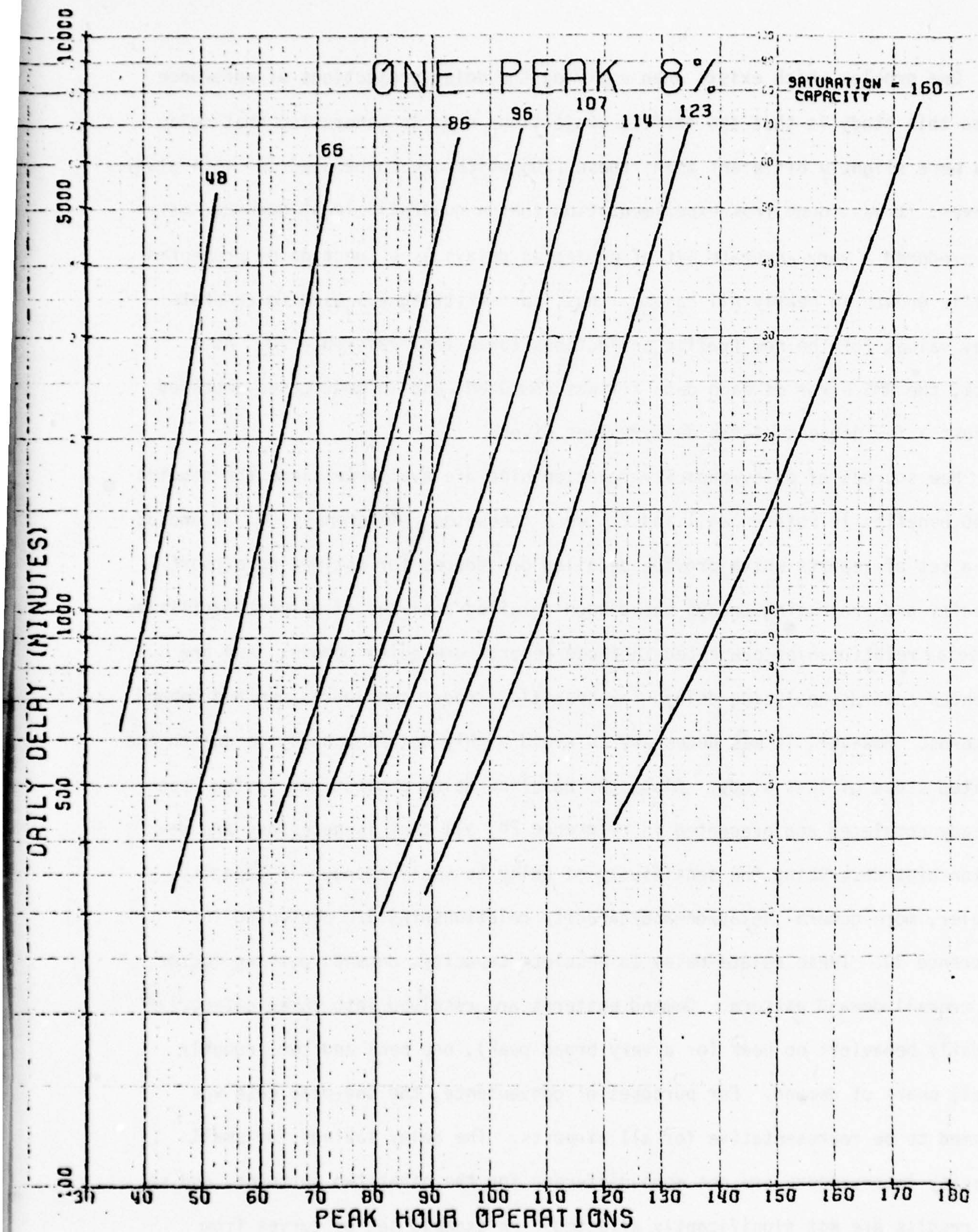


Figure 3.1 Relationship of Delay to Demand: 8% Peaking Factor (Reference 33)

quite laborious given the number of airports (29), cases (three ATC configurations with and without RNAV or 4D), and years (five--1980, 1985, 1990, 1995 and 2000) for which the computation must be made. The procedure involves first converting the delay projection from reference 28 to daily delay, and computing the peak hour operations from the demand projections [20] and peaking factor [28], and then locating a point on the graph for that peaking factor, such as Figure 3.1 for an eight percent peaking factor. Naturally, since the peaking factors were usually fractional, the process must be performed twice using the nearest whole numbers and the results are then interpolated. The point on the graph thus represents a value for capacity, derived from the sloping constant capacity lines as shown in Figure 3.1. Delay savings impact is derived as follows: First the capacity figure is adjusted upwards the specified percentage (3.26% for RNAV or 4.6% for 4D RNAV arrival capacity impact). Keeping peak hour operations constant, a new daily delay value is found on the graph corresponding to the higher capacity. The daily delay savings benefit is the old delay minus the new delay, divided by two since only arrivals are affected. This savings is then converted to an annual value.

The usage of historic peaking factor data in this analysis does create a problem since, as the level of traffic grows over a period of time at an airport, the peak hour percentage tends to drop (the so-called "peak-flattening" effect). This effect was ignored since there is no direct data avaiable which describes the peak-flattening to be expected at these airports. However, to avoid extreme cases, any historic peaking factor greater than 9% was set to 9%, since greater peaks are hard to sustain as traffic grows. This affected five of the twenty-nine airports studied.

There is one significant problem associated with utilizing the delay projection data contained in reference 28. In that study a delay model was applied directly to the capacity and demand data provided to the analysts, regardless of the magnitude of the delays which resulted. In many cases mean delay per operation values of 10, 20 or 30 minutes resulted. Note that these are delay

per operation values -- not delay per aircraft delayed, which will, of course, be much higher. The largest mean delay per operation listed was 134 minutes. Obviously, as mean delays grow, they will reach an intolerable limit beyond which traffic growth would cease. Since no such limits were applied in reference 28, the benefit to RNAV and 4D which would result from manipulations of that data would show a larger savings than would actually be realizable. That is to say, since the stated delays are so large as to be unrealistic, the delay savings due to capacity increases would also be unrealistic. Therefore, demand limiting was applied to those airports so affected to bring delays down to a more reasonable level.

In order to select an appropriate limiting level of average delay per operation, historic delay data [34, 35] has been reviewed. The highest average delays found are listed in Table 3.2, the maximum of which is 7.13 minutes. Since delays could probably climb higher yet before growth totally stopped, a level of ten minutes per operation was selected as the absolute maximum value for delay. Demand limiting was applied, through the curve fit process described earlier, to limit delays at that value. However, it was applied only to those cases which are appropriate considering the UG3RD implementation schedule. For example, the base case (continued ARTS III) projections were only limited out to 1985, not 2000, since the near-term improvements will be in effect by 1985. However, once a limit for a given year is reached, in the base case for example, the same traffic level was applied to the UG3RD improvement cases for that year so that all cases are compared on an equivalent demand basis.

The delay savings computation process was soon found to be extremely laborious. In order to reduce the effort involved, a new set of curves were derived from the delay/demand/capacity curves, and are shown in Figure 3.2. The new curves show the direct relationship between delay savings, daily delay

Table 3.2 Historic Delay per Operation Data at High Delay Airports

AIRPORT	DELAY PER OPERATION	YEAR
ATL	7.13 min.	1973
DEN	4.07	1973
EWR	4.89	1969
JFK	6.74	1969
JFK	6.10	1973
LGA	6.31	1969
LGA	5.46	1973
ORD	7.02	1973
PHL	4.59	1973

before capacity adjustment, and peak hour operations. Two sets of curves were developed, one for the 3.26% capacity increase (RNAV), and one for the 4.6% increase (4D RNAV with M&S). An example (4.6% capacity increase for the 8% peaking factor) is shown in Figure 3.2. Using these curves it was possible to go directly from the given values for daily delay and peak hour operations to the desired quantity, daily delay savings.

Once delay savings have been projected at a given airport for a given year, it is of interest to express these results in terms of costs: aircraft operating costs and fuel consumption. This requires knowledge of the aircraft categories involved. Reference 20 provides projections of aircraft category mix at five year intervals at each airport. Presuming that all categories of aircraft are affected equally, this data serves as a basis for computing total lost dollars due to aircraft operating costs and fuel costs. In reference 1 the necessary data for performing this computation are developed. Fuel consumption data was taken from performance handbooks for aircraft types representative of each category, and are shown in Table 3.3. The flight condition assumed was a holding pattern configuration at 10,000 feet, with a relatively light aircraft weight assumed. Five categories are listed: 4EWB, 3EWB (four and three engine wide body transports), and 4ESB, 3ESB, 2ESB (four, three and two engine standard body transports). Also in that reference an effort was made to bound the range of costs

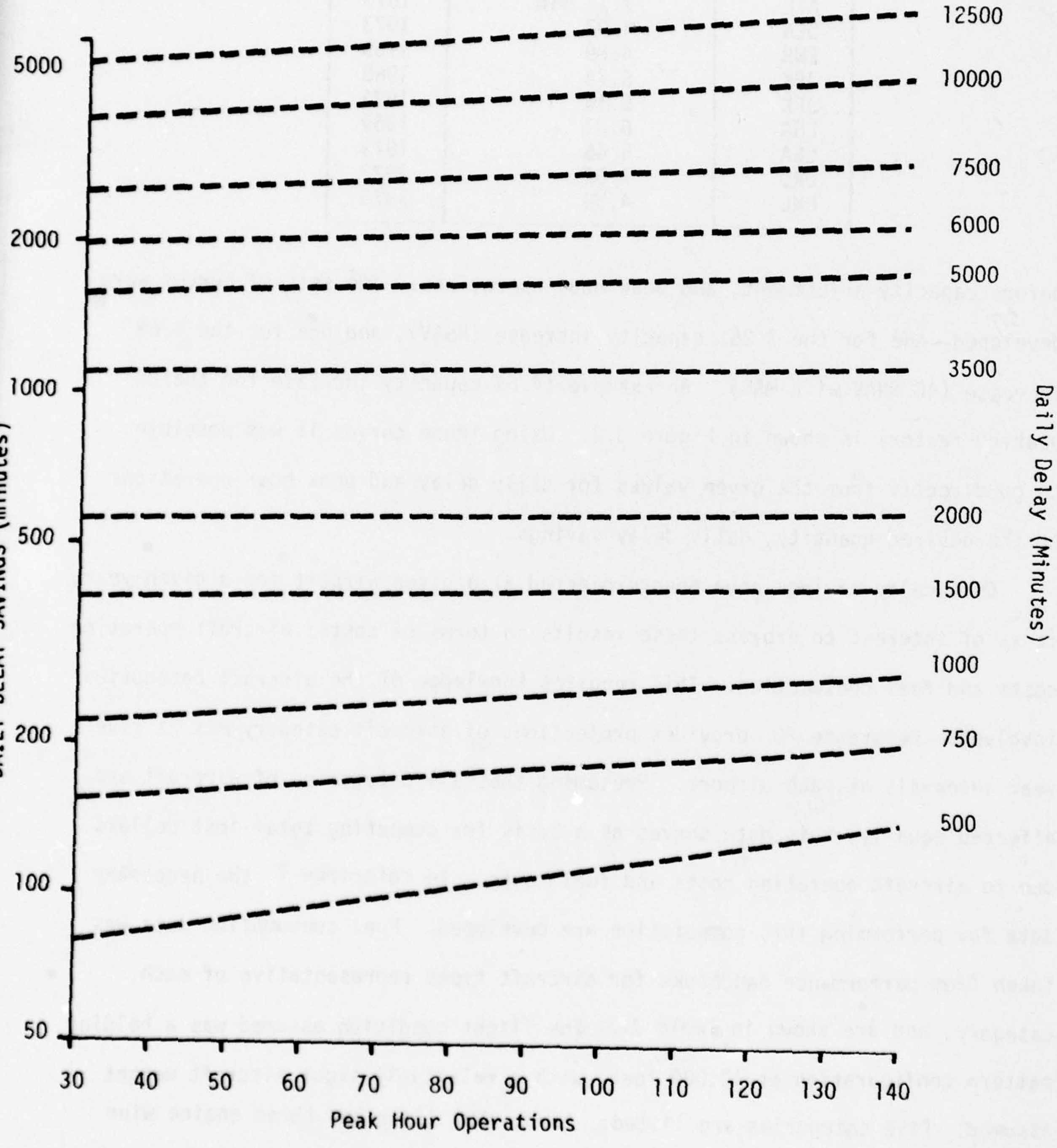


Figure 3.2 Delay Savings Relationship; 4.6% Capacity Improvement, 8% Peaking Factor

Table 3.3 Holding Fuel Flow

AIRCRAFT CATEGORY	WEIGHT (Klb)	FUEL FLOW (lb/min)
4EWB	400	245.3
3EWB	260	170.9
4ESB	180	148.1
3ESB	110	100.0
2ESB	70	66.4

which could be expected. Upper and lower bounds for fuel and airframe operating costs were used rather than single estimates because:

1) It is difficult to predict the level to which oil prices will rise over and above general inflation, and

2) Different airlines treat incremental (e.g., delay-related) aircraft operating cost accounting in different ways, with some being more conservative in describing such costs.

Therefore, upper and lower values of \$0.36 and \$0.24 per gallon of fuel were selected. Currently, airlines are paying in excess of \$0.30 per gallon.

Upper and lower bounds of aircraft operating costs (less fuel) were selected for each aircraft category in reference 1. CAB data (1975) reported by the airlines was used as the basis for the values. The high cost assumption treated aircraft operating costs as being total DOC less fuel costs. The low cost bound treated aircraft operating cost as being total DOC less fuel, depreciation and rentals, with the remainder diminished an additional 20%. The resulting values are given in Table 3.4.

Table 3.4 Aircraft Hourly Cost Values Used in Projections

CATEGORY	4EWB	3EWB	4ESB	3ESB	2ESB
High (DOC less fuel)	\$1810	\$1307	\$773	\$612	\$544
Low (less Dep. + Rentals + 20%)	899	648	484	370	343

3.2 TERMINAL DELAY SAVINGS

The projected delay savings due to RNAV or 4D (with M&S) at each of twenty-nine high delay airports has been calculated at five-year intervals starting in 1980. These savings are based on the overall average delay per operation projections stated in Table 3.6, and peak hour operations data derived from Table 3.5. The methodology of Section 3.1 was used. The results, in terms of daily delay savings, are shown in Table 3.7. Using the fuel consumption and cost data in Tables 3.3 and 3.4 and aircraft category mix projections from reference 20 for each airport, the fuel, fuel cost and time cost projections for each airport, and in total, have been computed. A phased implementation of the UG3RD features and RNAV has been modeled in the following way to generate year-by-year delay savings projections according to the prescribed RNAV and UG3RD implementation schedules:

1) Linear interpolation is used to fill in the five-year intervals
2) RNAV implementation year for each terminal are as shown in Table 3.7 (reference 1)
3) RNAV equipage is implemented uniformly from 1982 to 1985 (approximation to schedule in reference 1) -- benefits are assumed in proportion to percent equipped
4) Near-term UG3RD improvements are phased-in uniformly from 1981 to 1985
5) 4D RNAV M&S environments are assumed to be implemented in 1986 at all 29 terminals
6) Remaining UG3RD improvements are phased-in from 1986 to 1990.

Table 3.5 Annual Traffic Demand (thousands), Limited to Yield 10-Minute Maximum Delay per Operation

AIRPORT	YEAR				
	1980	1985	1990	1995	2000
ATL	619	680*	680*	680*	680*
CLE	310	330*	330*	330*	330*
CVG	189	252	332	389*	389*
DAL	300	300	300	300	300
DFW	428	540	600	600	600
DTW	315	340	340	340	340
EWR	255	328	341*	341*	341*
IAH	238	292	349	374	399
IND	266	332	360	360	360
LAS	381	407	419	431	443
LAX	600	600	600	600	600
MCI	222	271	322	363	388
MEM	371	490	639	712	737
MIA	415	531	600	600	600
MSP	290	362	440	516	519*
MSY	191	237	285	332	375
PHL	385*	385*	385*	385*	385*
PHX	619	627*	627*	627*	627*
PIT	368	415	431	447	463
SEA	206	248	316	381	422
STL	396*	396*	396*	396*	396*
TPA	269	355	453	548	643
BOS	334	374*	374*	374*	374*
DCA	341	341	341	341	341
DEN	461*	461*	461*	461*	461*
JFK	393*	393*	393*	393*	393*
LGA	363*	363*	363*	363*	363*
ORD	707*	707*	707*	707*	707*
SFO	376*	376*	376*	376*	376*

*These values reduced to limit delay to 10 minutes

Table 3.6 Delay per Operation Projections Without RNAV (minutes)

AIRPORT	BASE CASE		NEAR-TERM IMPROVEMENTS			ALL IMPROVEMENTS				PEAKING FACTOR (%)
	YEAR		YEAR			YEAR				
	1980	1985	1980	1985	1990	1985	1990	1995	2000	
ATL	6.68	10.03	5.46	6.56	6.56	3.23	3.82	3.82	3.82	7.5
CLE	4.34	10.17	4.71	7.48	7.48	4.00	4.00	4.00	4.00	11.5*
CVG	1.66	3.35	1.28	2.93	8.06	2.52	6.07	10.02	10.02	8.5
DAL	2.00	2.00	2.33	2.33	2.33	3.51	3.51	3.51	3.51	7.5
DFW	2.08	3.98	1.99	3.59	4.77	2.98	3.68	3.68	3.68	8.1
DTW	1.01	1.07	1.26	1.39	1.39	1.19	1.19	1.19	1.19	8.0
EWR	3.33	9.33	2.50	8.04	10.02	5.43	6.12	6.12	6.12	8.6
IAH	1.22	1.97	1.11	1.86	2.86	1.67	2.27	2.54	2.80	7.0
IND	2.25	5.42	2.09	4.61	6.24	4.25	5.03	5.03	5.03	8.8
LAS	4.34	6.03	3.86	5.12	5.80	3.43	3.61	3.80	3.99	8.7
LAX	5.61	5.61	4.23	4.23	4.23	1.86	1.86	1.86	1.86	9.7*
MCI	1.16	1.88	1.17	1.84	2.74	1.61	2.36	3.13	3.68	9.6*
MEM	1.23	2.68	1.44	2.64	5.00	2.32	3.76	4.60	4.91	11.3*
MIA	3.15	5.99	2.33	3.59	4.79	3.88	4.97	4.97	4.97	8.9
MSP	2.05	4.33	2.08	4.01	7.99	3.73	6.32	9.86	10.02	8.5
MSY	1.16	2.42	1.42	2.43	4.60	1.91	3.47	6.00	9.19	7.9
PHL	9.94	9.94	9.22	9.22	9.22	9.00	9.00	9.00	9.00	7.7
PHX	9.43	10.02	8.00	8.46	8.46	6.15	6.15	6.15	6.15	7.7
PIT	2.88	4.35	2.83	4.00	4.49	3.63	3.85	4.08	4.30	7.8
SEA	2.30	4.25	2.11	3.50	7.14	2.15	3.62	5.76	7.47	8.0
STL	9.98	9.98	9.50	9.50	9.50	9.00	9.00	9.00	9.00	8.4
TPA	0.45	1.49	0.81	1.48	3.26	1.58	2.68	4.19	6.14	9.0
BOS	3.03	9.96	2.88	8.22	8.22	4.81	4.81	4.81	4.81	8.1
DCA	4.49	4.49	4.88	4.88	4.88	4.64	4.64	4.64	4.64	7.2
DEN	10.03	10.03	8.12	8.12	8.12	3.88	3.88	3.88	3.88	9.5*
JFK	10.00	10.00	8.00	8.00	8.00	6.00	6.00	6.00	6.00	7.8
LGA	10.04	10.04	9.33	9.33	9.33	8.69	8.69	8.69	8.69	7.9
ORD	9.97	9.97	8.00	8.00	8.00	6.00	6.00	6.00	6.00	6.8
SFO	10.07	10.07	9.07	9.07	9.07	7.00	7.00	7.00	7.00	8.6

*limited to 9.0%

Table 3.7 Daily Delay Savings with RNAV & 4D RNAV
(minutes)

AIRPORT	BASE CASE			NEAR-TERM IMPROVEMENTS				ALL IMPROVEMENTS				RNAV
	RNAV 1980	RNAV 1985	4D 1985	RNAV 1980	RNAV 1985	4D 1985	4D 1990	4D 1985	4D 1990	4D 1995	4D 2000	IMPL. YEAR
ATL	3100	4850	7900	2630	3400	5970	5970	2300	2900	2900	2900	1982
CLE	780	2300	4350	850	1540	2620	2620	1180	1180	1180	1180	1984
CVG	132	442	615	95	385	548	2785	435	1930	5100	5100	1985
DAL	313	313	434	377	377	509	509	823	823	823	823	1983
DFW	559	1599	2250	542	1473	1991	3379	1530	2378	2378	2378	1983
DTW	155	192	244	206	256	323	323	273	273	273	273	1984
EWR	436	1928	3262	298	1672	2708	3960	1628	2030	2030	2030	1982
IAH	111	296	380	96	277	358	784	305	585	745	915	1984
IND	301	1140	1740	279	923	1390	2430	1256	1822	1822	1822	1986
LAS	1080	1734	2931	950	1426	2322	2851	1398	1528	1732	1965	1984
LAX	3200	3200	4350	2200	2200	2900	2900	1070	1070	1070	1070	1982
MCI	110	260	370	110	250	360	695	283	580	1000	1440	1984
MEM	248	980	1260	305	950	1220	3950	1030	2650	4300	5100	1985
MIA	967	2584	6555	654	1525	2871	6301	3222	3222	3222	3222	1983
MSP	317	1005	1435	320	932	1295	4740	1210	3495	6800	6950	1984
MSY	84	281	455	116	285	484	1159	329	777	1860	3612	1984
PHL	2450	2450	4280	2310	2310	3900	3900	3750	3750	3750	3750	1984
PHX	3490	3550	8750	3118	3270	7300	7300	4710	4710	4710	4710	1985
PIT	671	1290	1692	661	1142	1500	1868	1348	1518	1734	1920	1984
SEA	225	565	830	200	450	655	2110	375	940	2100	3280	1984
STL	2520	2520	4550	2400	2400	4340	4340	4020	4020	4020	4020	1984
TPA	47	285	380	91	284	378	1640	415	1280	2530	5330	1984
BOS	610	2180	4030	570	1870	3140	3140	1670	1670	1670	1670	1983
DCA	1016	1016	1332	1126	1126	1518	1518	1392	1392	1392	1392	1983
DEN	3970	3970	6250	3050	3050	4600	4600	1850	1850	1850	1850	1983
JFK	2380	2380	4370	1990	1990	3220	3220	2310	2310	2310	2310	1982
LGA	2180	2180	3940	2060	2060	3610	3610	3230	3230	3230	3230	1982
ORD	7650	7650	9990	6100	6100	7970	7970	5680	5680	5680	5680	1982
SFO	2510	2510	4460	2310	2310	3860	3860	2750	2750	2750	2750	1983

The results, in terms of fuel savings and time cost savings, are listed in Table 3.8. Listed at the bottom are the grand totals, which show that the 1976 present value equivalent to the savings through the year 2000 should range between $570 million and $962 million, depending on whether one prefers the low or high cost assumptions discussed at the end of Section 3.1.2. A discount rate of 10% was used in the present value analyses.

While the value of total fuel consumption should be discounted to present value for cost analysis purposes, it is also of interest to state the total fuel savings in terms of gallons, since it is a scarce resource. The total is 3.77 billion gallons of fuel saved, which is quite significant in comparison to the total air carrier fuel consumption for 1975 (from CAB data) which was 7.28 billion gallons. A graph of annual fuel savings is shown in Figure 3.3. The sharp rise in savings in 1982 is due to the assumption that RNAV is fully implemented by 1985. Savings drop slightly from 1985 to 1990, since overall delays are reduced by the long-term improvements which are implemented by 1990. After 1990 delays, and delay savings due to RNAV, again start to rise.

All of the RNAV delay and fuel savings results discussed in this section are sensitive to factors such as variations in implementation schedules. In particular, if UG3RD improvement schedules slip, RNAV impact will be greater. Should the RNAV schedule slip, some RNAV benefits will be lost. Also, other factors such as overall traffic growth rate are important. Changes in growth rates directly affect delays and, therefore, RNAV delay savings.

Table 3.8 Annual Fuel and Time Delay Savings

YEAR	FUEL SAVINGS (millions of lbs)	TIME COST SAVINGS		TOTAL
		LOW $*	HIGH $*	
1982	94.	$ 6.2M	$ 10.9M	
'83	293.	19.3	34.2	
'84	592.	39.6	78.3	
'85	876.	58.9	103.4	
'86	1413.	95.2	167.4	
'87	1394.	93.9	165.5	
'88	1356.	91.3	161.5	
'89	1301.	87.6	155.3	
1990	1227.	82.7	146.8	
'91	1290.	86.7	154.3	
'92	1353.	90.7	161.9	
'93	1416.	94.7	169.4	
'94	1479.	98.7	176.9	
'95	1542.	102.7	184.4	
'96	1594.	105.8	190.5	
'97	1646.	108.8	196.5	
'98	1698.	111.9	202.5	
'99	1750.	114.9	208.6	
2000	1802.	118.0	214.6	
LOW $ TOTAL*	$ 904.M	$1608M		$2512M
HIGH $ TOTAL	1358.M		$2883M	4241M
LOW $ 1976 P.V.	$204.9M	$365.5M		$570.4M
HIGH $ 1976 P.V.	307.7M		$654.2M	961.9M

*Refers to the low and high fuel/time cost assumptions discussed in Section 3.1.2.

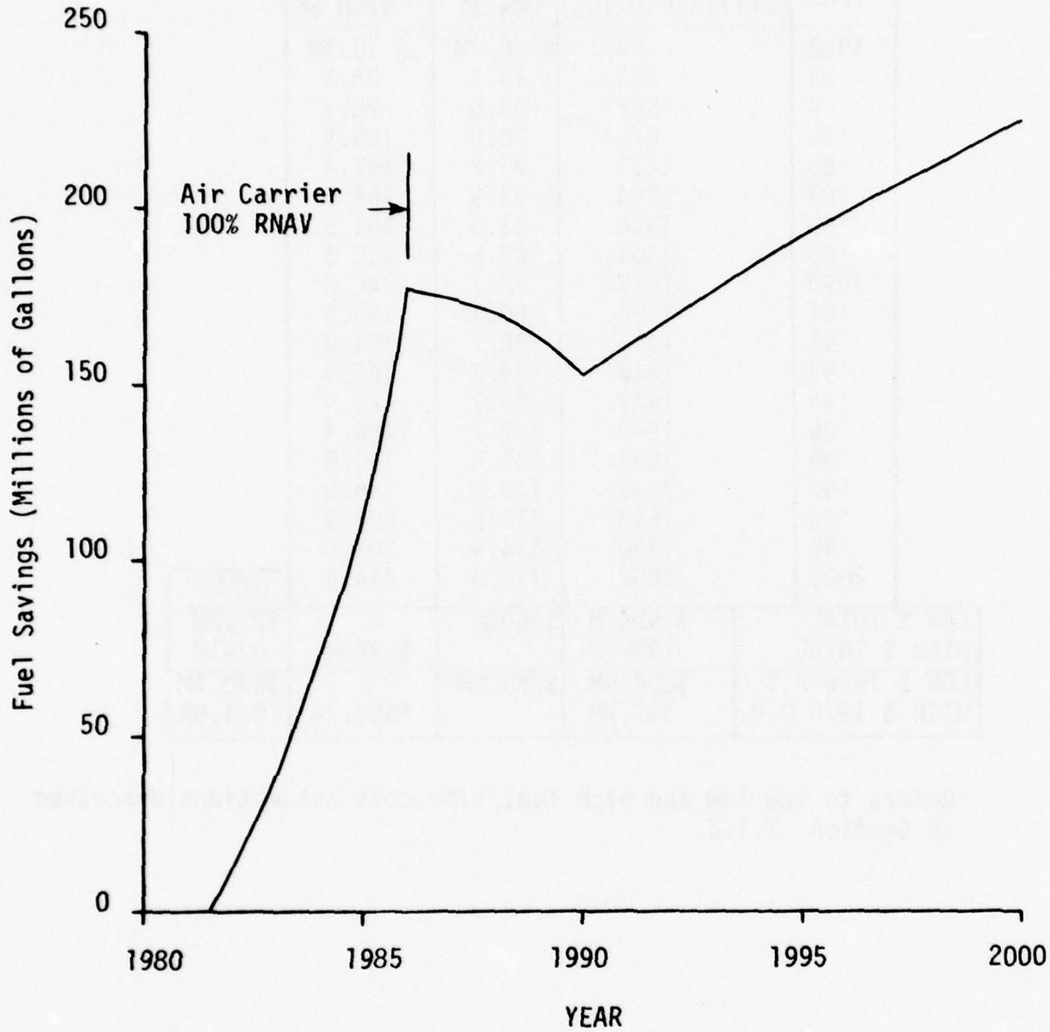


Figure 3.3 Annual Arrival Delay Fuel Savings Results

3.3 ENROUTE CAPACITY AND DELAY IMPLICATIONS OF RNAV

In this section the ability of RNAV routes and procedures to enhance enroute system capacity are discussed. The resulting potential impacts on enroute delays are introduced, although no general projections of enroute delay savings have been developed, for reasons which are explained in the following section.

3.3.1 Potential for Enroute Capacity Improvement

There are two basic mechanisms through which RNAV capability can enhance enroute capacity, where capacity is defined as the ability of the enroute environment (route structure and ARTCC capabilities) to accept departures and route aircraft to their intended destinations with minimal delay. The first mechanism involves the route structure itself. RNAV provides several capabilities that can serve to enhance the capacity of the route structure:

- Greater number of routes in a charted route structure environment.
- Elimination of splayed airspace requirement, allowing higher route density in certain areas.
- Ability to designate precise holding points at any desired location.
- Direct routes, and more nearly optimum selection of best-wind routes.

The second capacity enhancement mechanism involves the ability of RNAV to reduce controller workload and increase sector capacity, as explored in detail in Section 2.2. In that section it was shown that RNAV could positively impact all three categories of controller workload: traffic structuring, conflict processing and, to a minor extent, surveillance.

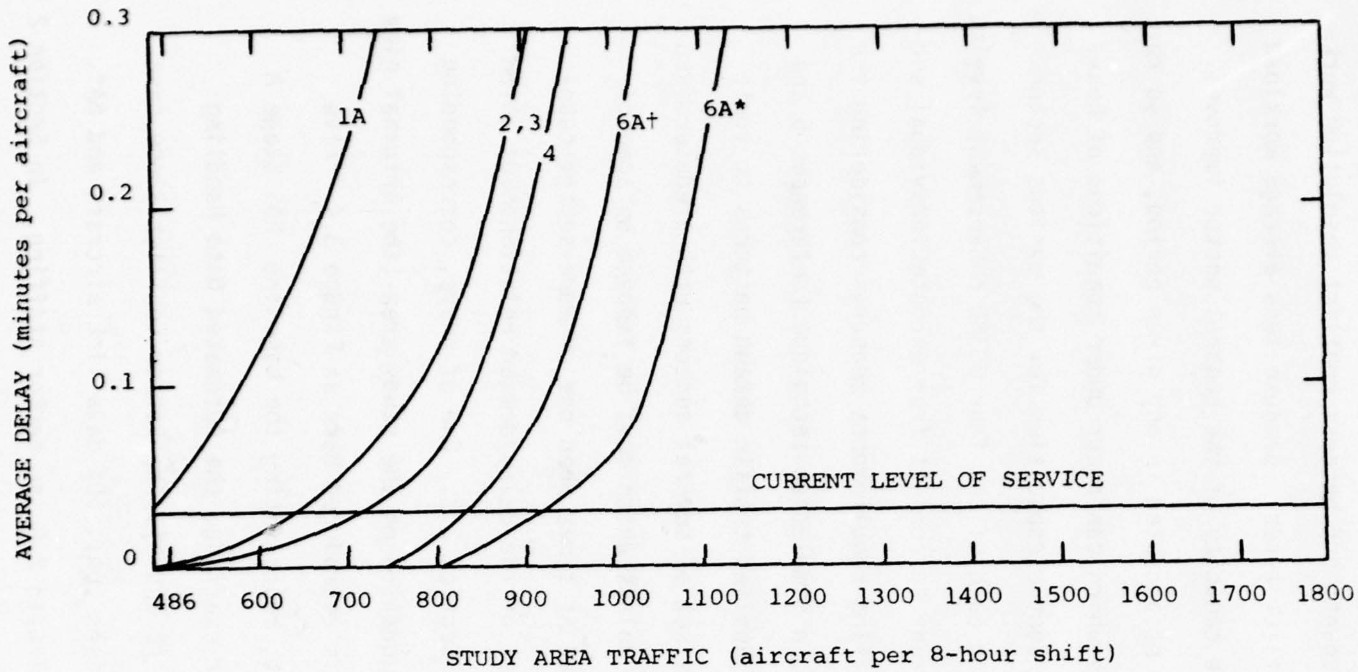
There is one complicating factor: If an attempt were made to increase airspace capacity by adding more RNAV routes, the ability of the sectors involved to handle increased traffic may not be sufficient to service the new capacity. Furthermore, splitting sectors in order to reduce sector traffic counts given the higher route capacity would provide sharply diminishing productivity returns. Ultimately, the ability of the ATC system itself to handle traffic would limit traffic capacity, even though additional route capacity may be available. Therefore, it is not appropriate to treat RNAV route structure capacity improvements independently of controller workload factors, since the two factors interact.

Referring to the terminal area capacity study (Section 3.1), it was found that an RNAV arrival capacity effect exists, demonstrated by real time simulation, which is essentially independent of the controller workload impact of RNAV which was demonstrated through the use of the SRI workload analysis techniques. Therefore, RNAV delay reduction and controller productivity benefits could be calculated independently. Since the issues of traffic capacity and controller workload effects are interrelated in the enroute case, the calculation of those delay benefits which would arise independent from the RNAV productivity effect is a very difficult problem. This is particularly true in a period of rising traffic demand where ATC limitations rather than route structure limitations will constrain capacity. Therefore the delay impact discussion, presented in Section 3.3.2 below, concentrates on the enroute delay impact of RNAV due to controller workload improvements.

3.3.2 Enroute Delay Implications of RNAV

The impact of RNAV on controller workload and sector capacity was presented in detail in Section 2.2. Briefly, the major impact areas

were the elimination of radar vectors and associated heading data interchanges, and a reduction in conflict processing workload. The conflict situation is improved both because the RNAV route structure reduces expected conflict situation count, and because conflict resolution workload is reduced for some conflict types. Because less average workload is required per aircraft, the capacity of the control sector improves. This allows more aircraft to be accepted in any given period, and so reduces enroute aircraft delays which can occur under conditions of heavy demand. In Section 2.2, new sector capacities for the various sector types were derived considering each of the four UG3RD enhancement levels, with and without RNAV. In order to convert from enroute individual sector capacity measures to staffing requirements measures considering the interactions of many sectors, a simulation technique (references 5 and 23) was developed by SRI. It applies traffic demand patterns to route networks through a contiguous set of several sectors with predetermined capacities, and measures the delays which must be imposed on some of the aircraft entering the area at times when one or more sector capacities are exceeded. Examples of the delay/demand relationships which result are shown in plots in Section 2.2. One of these, corresponding to the original sector configuration of the study area (the original nine sectors -- none are split), is reproduced here as Figure 3.4. Five curves are shown in this plot, representing the baseline NAS Stage A case (1A) with 2.5 man sector staffing, the Automated Data Handling and Local Flow Control cases (2 and 3), the Sector Conflict Probe case (4) and the DABS Data Link cases (6A+, 50% data link aircraft and 6A*, 100% data link aircraft), all with 2.0 man sector staffing. In Section 2.2 the 1B and 6B cases were examined, but did not apply for the traffic levels

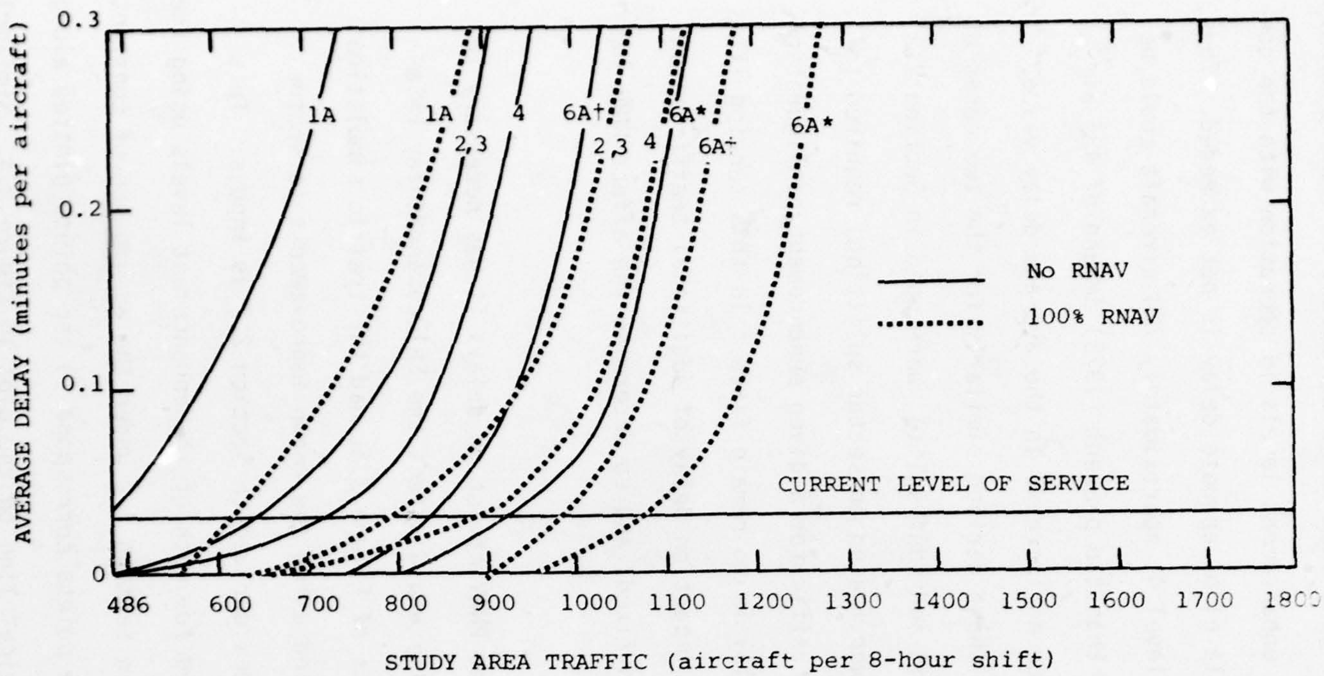


*100% data link aircraft
†50% data link aircraft

Figure 3.4 Relationship of Per Aircraft Delay to Study Area Traffic Demand

studied. Note that there is a horizontal line on Figure 3.4 labeled "current level of service" at an average delay of 0.03 minutes per aircraft as measured by the simulation. This figure then shows the amount of traffic which may be serviced with each of the enhancement levels in operation with the constraint that the current level of enroute delay is not exceeded. Thus, under system enhancement level 4, approximately 720 aircraft could be serviced per shift rather than the present (1975) demand of 486 aircraft, and still experience no increase in the average delay value. These relationships, along with those derived similarly for the two cases of sector splitting (50% split and 100% split), were used in Section 2.2 for determining the manpower (based on sector splitting) required to service a given level of traffic for a given enhancement configuration presuming that average delay is to remain fixed. In this section it is of interest to assess the impact on delay of additional traffic given that manpower is to remain fixed, and to determine the effect RNAV has on those levels.

In order to assess the RNAV effect on delays it was necessary to estimate how RNAV capability would affect the SRI demand/delay relationship simulation results of Figure 3.4, had the traffic simulation been available to be applied using the known improvements to sector capacity which RNAV provides derived in Section 2.2 as inputs. This estimation was accomplished for each of the enhancement levels using the traffic levels developed in Section 2.2 under the assumption of constant per aircraft delay. These points correspond to the points plotted along the "current level of service" line on the plot in Figure 3.4. Similarly, the impact on traffic handling capabilities of RNAV for each enhancement level has been computed in the manner disucssed in Section 2.2. These values are plotted along the "current level of service" line on the plot



*100% data link aircraft
†50% data link aircraft

Figure 3.5 RNAV Impact on Per Aircraft Delay

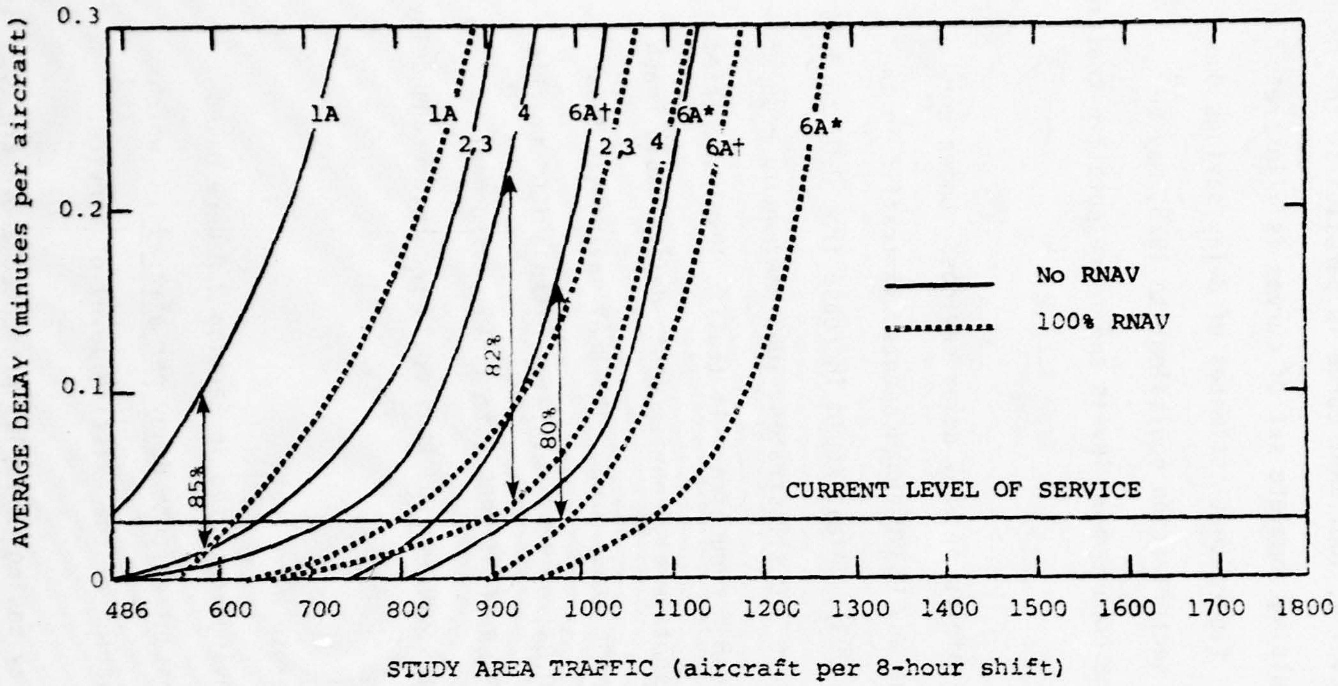
in Figure 3.5. The remaining parts of these 100% RNAV case curves were derived simply by using the same slopes as the enhancement levels to which they correspond (e.g. the level 4, 100% RNAV curve is parallel to the level 4, no RNAV curve). The resulting complete set of curves is illustrated in Figure 3.5. It is from this figure that estimates of delay savings due to RNAV, given staffing and sectorization equivalent to 1975, may be computed assuming any of the enhancement levels and representative traffic demand values.

Figure 3.6 gives some examples of RNAV delay savings. Under current sectorization and without any UG3RD enhancements, if traffic in the study area increases 20% (to 583), delays would increase from 0.03 to 0.10 minutes per aircraft. As Figure 3.6 illustrates, 100% RNAV would reduce the delay to 0.015 minutes, an 85% reduction. If traffic level increased by 90% (to 923) in an enhancement level 4 environment, delays would reach 0.225 minutes per aircraft in the study area. The RNAV savings in this case would be a reduction to 0.04, or 82%. Likewise given a 100% traffic increase (to 972) in the level 6A+ (50% DABS data link) environment, delays would reach 0.16 minutes, while 100% RNAV would reduce average delay to 0.03 minutes, an 80% savings.

It is important to reiterate here that:

1) The RNAV staffing savings computed in Section 2.2 were based on assumption of constant enroute <u>delay per aircraft</u>, which represents a continuation of the existing level of service.

2) The RNAV enroute delay savings examples presented above are based on an assumption of constant staffing which could result in a degradation in level of service provided.



*100% data link aircraft
†50% data link aircraft

Figure 3.6 Typical RNAV Enroute Delay Savings Examples

As a result, no attempt has been made here to project RNAV enroute delay savings benefits for all of the Atlanta center sectors, or for the remaining centers, for the 1975 to 2000 time frame. The reasoning used was that the benefit values which would result would not be compatible with the staff savings benefits projections made in Section 2.2, since a degradation in level of service provided would have to be assumed. It would, of course, be possible to postulate a scenario whereby constraints on staff size are presumed. RNAV enroute delay savings would result under such circumstances. However, this would not be consistent with the assumptions of the remainder of the study, and so was not done.

4.0 CONCLUSIONS

The major points of interest demonstrated through the analyses performed as a part of this study effort are stated below.

4.1 CONTROLLER WORKLOAD, SECTOR CAPACITY AND STAFF REQUIREMENT RESULTS

- The analyses conducted essentially reaffirm the results presented in references 4 and 5 concerning the impact of the UG3RD enhancement features* other than RNAV on controller workload, sector capacity and controller productivity.

- In light of the ongoing analyses of the potentially beneficial effects of RNAV, and the results of recent simulation studies, the treatment of RNAV in the above-referenced studies inadequately reflects its true potential contribution to workload savings, etc.

- RNAV has been demonstrated to be a major source of terminal and enroute controller workload savings. In the terminal case, it is equivalent to other major workload-reducing UG3RD features with the exception of DABS/Control Message Automation, which on the average provides one-third again as much workload reduction as RNAV. In the enroute case the three major workload reducers (Automatic Flight Data Handling, RNAV, and DABS/Control Message Automation) make roughly equivalent contributions to the reduction of workload.

*Exceptions were taken to the Metering and Spacing methodology, but with only minor influences on overall results.

- The analyses have shown that savings in real controller workload can be translated into improvements to average controller productivity through improvements to control sector capacity. The mechanisms studied included changing the staffing for individual sectors (terminal and enroute) and splitting sectors (enroute).

- Based on assumed implementation scenarios for the UG3RD features and RNAV, the following overall results in man years for the 19-year RNAV implementation and usage period considered (1982-2000) were derived: Terminal (Twenty-eight terminal areas), 3715 man years (14%) or $92.1 million at 1975 salary levels; Enroute (all twenty centers), 20,498 man years (11%) or $508 million.

4.2 SYSTEM CAPACITY AND DELAY RESULTS

- RNAV has been shown to be a significant source of terminal arrival capacity improvement and delay reduction. The usage of RNAV procedures themselves has been demonstrated to produce a 3.26% arrival capacity improvement. After M & S procedures are implemented, this improvement would be supplanted by an improvement of approximately 4.6% through the use of 4D RNAV techniques.

- Based on the same assumed implementation scenario for UG3RD features and RNAV referred to above, RNAV reductions to delays would result in air carrier dollar savings over 19 years ranging from $2.5 to $4.2 billion dollars, depending on values assumed for fuel and aircraft time costs.

- The value of RNAV improvements to enroute control sector capacity was quantified in terms of controller staffing requirements reductions in the face of a growing traffic demand trend, assuming that the quality of service (mean enroute delay) provided remains constant. If, however, staff growth is constrained such that enroute delays grow, RNAV can cause very large reductions in these delays.

- The overall savings in fuel due to the usage of RNAV and 4D to improve terminal arrival capacity and reduce delays amounts to 3.77 billion gallons over the 19 year time period. This savings is equivalent to 52% of the total air carrier fuel consumption in 1975. An earlier study [1] indicates further fuel savings due to RNAV. In summary:

Terminal Delay Reduction:	3.77 b. gal.
Terminal Route Structure:	3.02 b. gal.
Enroute Route Structure:	3.73 b. gal.
VNAV-aided Descents:	0.83 b. gal.
TOTAL	11.35 b. gal.

This total is equivalent to 156% of the 1975 total air carrier fuel consumption.

REFERENCES

1. "Systems Integration: RNAV and the Upgraded Third Generation System", Bolz, E.H., et al, Systems Control, Inc. (Vt), December 1976, FAA-RD-77-22.

2. "Implementation of Area Navigation in the National Airspace System: an Assessment of RNAV Task Force Concepts and Payoffs", Clark, W.H., Bolz, E.H., et al, Systems Control, Inc. (Vt), December 1976, FAA-RD-76-196.

3. "Impact of RNAV on ATC Economics", Preliminary Report (unpublished), Bolz, E.H., Champlain Technology, Ind., Systems Control, Inc. (Vt), for FAA, SRDS, March 1973.

4. "Oakland Bay TRACON and Los Angeles TRACON: Case Studies of Upgraded Third Generation Terminal ATC Operational Impact", Couluris, G.J., Johnson, J.M., Stanford Research Institute, March 1977, FAA-AVP-77-23.

5. "Atlanta Center Upgraded Third Generation Enroute ATC System Operations: A Case Study", Couluris, G.J., Johnson, J.M., et al, Stanford Research Institute, March 1977, FAA-AVP-77-22.

6. "The Air Traffic Controller's Contribution to ATC System Capacity in Manual and Automated Environments", Volume I-Summary Report, Volume II-Appendicies, Volume III-Terminal Operations; Ratner, R.S., Williams, J.O., et al, Stanford Research Institute, June 1972, FAA-RD-72-63, I, II, III.

7. "Estimation of UG3RD Productivity Impacts", Rogers, J.M., January 1977, FAA-AVP-77-4.

8. "Comparative Cost Estimates of Productivity of UG3RD ATC Alternatives", Couluris, G.J., March 1977, FAA-AVP-77-24.

9. "Area Navigation/Vertical Area Navigation, Terminal Simulation", Crimbring, W., Maurer, J., April 1976, FAA-RD-76-28.

10. "Discount Rates to be Used in Evaluating Time-Distributed Costs and Benefits", Circular A-94 Revised, Office of Management and Budget, March 27, 1972.

11. "Analytical Study of Air Traffic Capacity in the New York Metropolitan Area", and "New York Air Traffic Capacity Study (Real Time Simulation)", Systems Research and Development Service and National Aviation Facilities Experimental Center, February 1970, FAA-RD-70-7.

12. "Economic Impact of Area Navigation", Volume I-Main Text, Bolz, E.H., Clark, W.H., et al, Champlain Technology Ind., Systems Control, Inc. (Vt), July 1974, FAA-RD-75-20.

13. "Controller Productivity Study, Enroute Control, Terminal Control, Flight Services", The Mitre Corporation, November 1971, MTR-6110.

14. "Controller Productivity in the Upgraded Third Generation Air Traffic Control System. Part I: Automation in the Pre-Data Link ERA", Keblawi, F.S., July 1976, FAA-EM-76-3.

REFERENCES
(Continued)

15. "Controller Productivity in the Upgraded Third Generation ATC System. Part II; Automation in the Data Link Era", Keblawi, F.S., the MITRE Corp., August 1976, MTR-7319.

16. "ARTS-III Enhancements Costs and Benefits", Willis, K., METIS Corp., September 1975, FAA-AVP-75-3.

17. "Preliminary Two-Dimensional Area Navigation Terminal Simulation", Maurer, J., O'Brien, P.J., et al, February 1975, FAA-RD-74-209.

18. "A Proposed Metering and Spacing System for Denver", Gados, R.G., et al, MITRE Corp., MTR-6865, March 1975.

19. "Terminal Area Design -- Analysis and Validation of RNAV Task Force Concepts", McConkey, E.D., Systems Control, Inc. (Vt), October 1975, FAA-RD-76-194.

20. "UG3RD Analysis Work, Program 1: Baseline and Implementation Scenario", by AVP-100, July 1975.

21. "Application of ATC Terminal Staffing Standard for PY 1976 (ADP RUN)", Air Traffic Service, FAA, 1976 (unpublished).

22. "Case Study of the Upgraded Third Generation Enroute ATC System Staffing Requirements for the Los Angeles Center", Couluris, G.J., Stanford Research Institute, June 1975, FAA-AVP-75-5.

23. "Capacity and Productivity Implications of Enroute Air Traffic Control Automation", Couluris, G.J., Ratner, R.S., et al, Stanford Research Institute, December 1974, FAA-RD-74-196.

24. "High-Altitude Area Navigation Enroute Simulation", Willett, Jr., F.M., NAFEC, FAA, January 1977 (Draft).

25. "Area Navigation High Altitude Payoff Analysis Enroute Fast Time Simulation Results", Cassell, R., Federal Aviation Administration, December 1975, FAA-RD-76-26.

26. "Longitudinal Separation Standards on Final Approach for Future ATC Environments", Sinha, A.N., Haines, A.L., MITRE Corp., October 1975, MTR-6979.

27. "Models for Runway Capacity Analysis", Harris, R.M., The MITRE Corporation, December 1972, MTR-4102.

28. "Estimation of UG3RD Delay Reduction", Rogers, R.A., Drago, V.J. et al, Battelle Columbus Laboratories, FAA-AVP-77-7, January 1977.

29. "Estimation of UG3RD Capacity Impacts", Smith, A., The MITRE Corp., FAA-AVP-77-9, January 1977.

30. "Techniques for Determining Airport Airside Capacity and Delay", Peat, Marwick, Mitchell & Co., et al, June 1976, FAA-RD-74-124.

REFERENCES
(Continued)

31. "Procedures for Determination of Airport Capa[illegible]", Peat, Marwick, Mitchell & Co., et al, June 1976.

32. "Supporting Documentation; Procedures for De[illegible]ining Airport Capacity", Peat, Marwick, Mitchell & Co., et al, June [illegible]76.

33. "A Handbook for the Estimation of Airside [illegible]elays at Major Airports", (Quick Approximation Method), Odoni, A.R., Kivestu, P., Massachusetts Institute of Technology, June 1976, NAS[illegible]R-2644.

34. "Terminal Area Airline Delay Data, 19[illegible]969", Galbreath, A., Warfield, [illegible] Air Traffic Service, FAA, September [illegible]0.

35. "[illegible]line Delay Data, 1970-1974", O[illegible]ations Research Branch, Air Traffic [illegible]ce, FA[illegible] February 1975.

REFERENCES
(Continued)

31. "Procedures for Determination of Airport Capacity", Peat, Marwick, Mitchell & Co., et al, June 1976.

32. "Supporting Documentation; Procedures for Determining Airport Capacity", Peat, Marwick, Mitchell & Co., et al, June 1976.

33. "A Handbook for the Estimation of Airside Delays at Major Airports", (Quick Approximation Method), Odoni, A.R., Kivestu, P., Massachusetts Institute of Technology, June 1976, NASA CR-2644.

34. "Terminal Area Airline Delay Data, 1964-1969", Galbreath, A., Warfield, R.M., Air Traffic Service, FAA, September 1970.

35. "Airline Delay Data, 1970-1974", Operations Research Branch, Air Traffic Service, FAA, February 1975.

BIBLIOGRAPHY

1. "O'Hare Delay Task Force Study", Volume II-Technical Report, Chicago O'Hare International Airport, Federal Aviation Administration, City of Chicago-Department of Aviation, The Airlines Serving O'Hare, July 1976, FAA-AGL-76-1.

2. "Airport Capacity Criteria Used in Long-Range Planning", Advisory Circular 150/5060-3A, Department of Transportation, Federal Aviation Administration, December 1969.

3. "A Methodology for Determining Airport Capacity-JFK Application", Department of Transportation, Federal Aviation Administration, Office of Management Systems, January 1972.

4. "New York Airports Improvement Task Force, Kennedy and LaGuardia Runway Capacities", Office of Systems Engineering Management, FAA, and Peat, Marwick, Mitchell & Co., August 1976.

5. "Econometric Estimates of Air Traffic Control Productivity and Other Parameters for Evaluating the UG3RD ATC System", Administrative Sciences Corporation, February 1976 (Draft).

6. "Engineering and Development Program Plan-Concepts, Design and Description for the Upgraded Third Generation Air Traffic Control System", The MITRE Corporation, August 1972, FAA-ED-01-1A.

7. "An Overview and Assessment of Plans and Programs for the Development of the Upgraded Third Generation Air Traffic Control System", The MITRE Corporation, March 1975, FAA-EM-75-5.

8. "Engineering and Development Program Plan-Area Navigation", U.S. Dept. of Transportation, Federal Aviation Administration, September 1974, FAA-ED-04-02.

9. "Engineering and Development Program Plan-Enroute Control", U.S. Dept. of Transportation, Federal Aviation Administration, February 1975, FAA-ED-12-2A.

10. "Engineering and Development Program Plan-Terminal/Tower Control", U.S. Department of Transportation, Federal Aviation Administration, April 1973, FAA-ED-14-2.

11. "Aviation Forecast Fiscal Years 1976-1987", U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Policy, Aviation Forecast Branch, September 1975, FAA-AVP-75-7.

12. "IFR Aircraft Handled, Air Route Traffic Control Center-Fiscal Years 1975-1986", Department of Transportation, Federal Aviation Administration, Office of Aviation Policy, Aviation Forecast Branch, September 1974.

13. "Terminal Area Forecast-1976-1986", Department of Transportation, Federal Aviation Administration, Office of Aviation Policy, Aviation Forecast Branch, September 1974.

BIBLIOGRAPHY
(Continued)

14. "RNAV Impact on ATC Automation", Braff, R., Yezek, F.O., MITRE Corp., March 1974, MTR-6612.

15. "Cost Analysis of Electronic Tabular Display Subsystem Enroute ATC Operational Impact", Couluris, G.J., Petracek, S.J., Stanford Research Institute, for FAA, AVP, May 1977. (Draft)

16. "Summary of Eastern Air Lines Reported Delays and Delay Costs (1975)", Freer, D.W., Director, Office of Aviation Policy, Federal Aviation Administration, July 1976.

17. "Validation of the DELCAP Airport Simulation Model", Gilsinn, J.F., Institute for Basic Standards, National Bureau of Standards, July 1975, FAA-RD-75-154.

18. "Capacity Impact of Revising Aircraft Categories and Final Approach Separation Standards", Gupta, V.P., MITRE Corp., March 1976, MTR-7183.

19. "Concepts for Determination of Longitudinal Separation Standards on Final Approach", Haines, A.L., MITRE Corp., October 1975, MTR-7047.

20. "Concepts for Estimating Capacity of Basic Runway Configurations", Haines, A.L., Sinha, A.N., MITRE Corp., January 1976, MTR-7115.

21. "Capacity Assessment of Impact of Some of E&D Elements at Denver Stapleton International", Haines, A.L., MITRE Corp., September 1976.

22. "Area Navigation High-Altitude Network Study", Halverson, A.G., Woodson, F.B., et al, U.S. Dept. of Transportation, Federal Aviation Adminstration, February 1976, FAA-RD-76-6.

23. "Modeling Air Traffic Performance Measures. Volume I, Message Element Analyses and Dictionaries", Hunter, J.S., et al, Princeton University, July 1974, AD-782-437.

24. "Capacity Assessment of Impact of Some of E&D Elements at New York Airport (JFK, LGA)", Iyer, R.R., MITRE Corp., September 1976.

25. "Alternative Approaches for Reducing Delays in Terminal Areas", Meisner, M., Van Duyne, E., Faison, W., Dept. of Transportation, Federal Aviation Administration, Systems Research and Development Service, November 1967, FAA-RD-67-70.

26. "Automated Metering and Spacing with Area Navigation", Mohleji, S.C., MITRE Corp., June 1973, MTR-6431.

27. "A Study of Air Traffic Control System Capacity", Raisbeck, G., et al, Arthur D. Little, Inc., October 1970, AD-716-659.

BIBLIOGRAPHY
(Continued)

28. "Illustrative Applications of Air Traffic Control System Capacity Study Methodology", Raisbeck, G., Everett, J.L., et al, Arthur D. Little, Inc., November 1971, FAA-RD-71-113.

29. "On Modeling ATC Workload and Sector Capacity", Schmidt, D.K., Purdue University, Journal of Aircraft, Vol. 13, No. 7, July 1976.

30. "Estimation of UG3RD Safety Benefits", Simpson, T.R., Smith, A., et al, The MITRE Corp., January 1977, FAA-AVP-77-8.

31. "Advanced Productivity Analysis Methods for Air Traffic Control Operations", Tuan, P.L., et al, Stanford Research Institute, December 1976, FAA-RD-76-164.